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# The design and development of capacitive quasi-closed loop positional sensor

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The design and development of  
a capacitive quasi-closed loop  
positional sensor

by

Craig Alan Baack

A Thesis Submitted to the  
Graduate Faculty in Partial Fulfillment of the  
Requirements for the Degree of

MASTER OF SCIENCE

Major: Industrial Education and Technology

Signatures have been redacted for privacy

Signatures have been redacted for privacy

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Iowa State University  
Ames, Iowa

1986

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## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iv
CHAPTER I. INTRODUCTION	1
Problem of the Study	11
Purpose of the Study	11
Need for the Study	12
Assumptions of the Study	13
Objectives of the Study	14
Limitations of the Study	14
Hypotheses of the Study	15
Definition of Terms	20
CHAPTER II. LITERATURE REVIEW	23
CHAPTER III. METHODOLOGY OF THE STUDY	25
Theory of Construction for the	
Repeatability Experiment Apparatus	25
Procedure for the Repeatability Experiment	27
Theory of Construction for the	
Environmental Chamber Apparatus	31
Procedure for the Environmental Chamber Experiment	32
Method of Data Analysis	38
CHAPTER IV. FINDINGS OF THE STUDY	41
Overall Statistical Summary	41
Analysis of the Research Hypotheses	45

CHAPTER V. SUMMARY AND DISCUSSION OF THE RESULTS	56
Discussion of Research Hypotheses	56
Experimental Changes	62
Conclusions of the Study	68
Recommendations of the Study	69
Implications of the Study	70
BIBLIOGRAPHY	72
APPENDIX A. ANALOG TO DIGITAL CONVERSION	76
APPENDIX B. OPTICAL ENCODER DISK CONFIGURATIONS	81
APPENDIX C. FIGURES AND TABLES RELATING TO REPEATABILITY EXPERIMENT	86
APPENDIX D. FIGURES AND TABLES RELATING TO ENVIRONMENTAL EXPERIMENT	103
APPENDIX E. HARDCOPIES OF COMPUTER SOFTWARE	122



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## CHAPTER I. INTRODUCTION

The first one-half century after World War II has been a time of great material consumption by the world's population. Never before has an individual's desire for convenience, comfort, and economy been satisfied by such an abundance and diversity of products. This material opportunity came about because of the insatiable tastes of the consumer and the accelerating competition between the world's manufacturers.

The proof of this was shown by the world ranking of those nations that produced manufactured goods during the post-war period. For example, until 1970, most of the world's durable goods were produced in the United States or Europe. However, within the next decade, this hierarchy changed radically as East Asian countries, most notably Japan, began to dominate the marketplace. This abrupt switch was the result of lower labor costs, more sophisticated quality control methods, and an eager appetite for the development and utilization of new manufacturing technologies. The last point is most crucial, because technology provides an economical control of the product's uniformity and quality.

The means by which technology can do this is mysterious, because the machine tools used to make these products have changed very little over the last 80 years. Therefore, something else besides the machines themselves have changed. That something else is that the controls for these machines have become more accurate and more economical. Stated differently, the human operator's senses, hands, and decisions have yielded to electronic sensors, mechanical manipulators, and computer algorithms.

The critical word in the last sentence is 'sensor'. This is important because the sensor provides the positional feedback to the computer, which in turn directs the machine to accurately make the next move. With this in mind, it makes sense that the more accurate and reliable the sensor, the less chance there is for error, and therefore the increased chance for greater levels of quality. If this is true, then better products will be made from machines which have economical sensors that possess a high level of precision.

The theory behind a positional sensor, or sometimes known as an positional encoder, is similar to that found in any other type of electronic transducer. This means that any change in the physical world creates a corresponding change in the voltage, current, resistance, or other electrical entity of the sensor. In the case of an encoder, it is the change in distance which is symbolized by the electric entity.

If these entities were examined at any time during a given time interval, it would be noticed that their magnitudes changed in a smooth, continuous manner or in an abrupt manner. In other words, in a vanishingly small interval of time, the sensor's output can have one of an infinite number of values, or it can have a constant value derived from a fixed set of values (Fig. A.1, Appendix A). In electronic terms, the former condition is called an analog signal and the latter is called a digital signal. Since the theory of either type of data transmission is beyond the scope of this study, the reader was encouraged to read

Section 11.5 in Gothman (1982), Section 11-9 in Williams (1982), Chapter 4 in Malvino and Leach (1986), or any other introductory text in digital electronics.

The problem with analog and digital signals is that it is difficult to accurately convert from one type into another. This is acutely noticed when distant electronic information, in the form of an analog signal, must be processed by a digital computer. The cure for this conflict is to use a digital pattern to express the analog signal. The value of this digital pattern can in turn be transmitted through many channels or tracks. Therefore, for a given interval of time, a binary pattern, or binary code, of parallel pulse trains must be used to approximately describe the analog signal.

In general, the number of channels and type of code determine the accuracy of a digital signal. Specifically, the greater the number of channels, the greater the accuracy. This explains why most digital encoders use up to twenty-four binary channels or binary digits for coding schemes. In addition, the term 'binary digit' is contracted to the term called a 'bit', and the bit pattern for each increment is called a 'word' or 'byte' (Fig. A.2, Appendix A).

The codes used by most suppliers include natural binary, hexadecimal (hex), binary coded decimal (BCD), and Gray or Excess 3 (XS3) (see Malvino & Leach, 1986, pp. 123-154). A comparison table between all four is shown in Table 1. Each one has its own strengths and weaknesses depending on how it is used.



Table 1. Summary of Common Machine Codes

Decimal	Binary	Hexidecimal	BCD	Excess-3	Gray
0	0000	0	0000	0011	0000
1	0001	1	0001	0100	0001
2	0010	2	0010	0101	0011
3	0011	3	0011	0110	0010
4	0100	4	0100	0111	0110
5	0101	5	0101	1000	0111
6	0110	6	0110	1001	0101
7	0111	7	0111	1011	0100
8	1000	8	1000	1011	1100
9	1001	9	1001	1100	1101
10	1010	A	0001 0000	0100 0011	1111
11	1011	B	0001 0001	0100 0100	1110
12	1100	C	0001 0010	0100 0101	1010
13	1101	D	0001 0011	0100 0110	1011
14	1110	E	0001 0100	0100 0111	1001
15	1111	F	0001 0101	0100 1000	1000
16	0001 0000	10	0001 0110	0100 1001	0001 1000
17	0001 0001	11	0001 0111	0100 1010	0001 1001
42	0010 1010	2A	0100 0010	0111 0101	0011 1111

For example, natural binary code is the way discrete items are counted when using binary numbers. This makes it ideal for transferring information to electronic hardware counters, but it also makes it terrible for sensing position. The reason for this is if an encoder stops in the middle of an increment, the sensing element in it may interpret one of the most significant bits as being at logic high when it really is not. This may cause the computer to think the machine is in error by at most one-half of its working range.

Hexadecimal and BCD codes are the most frequently used codes. The reasons why are dependent upon the monitoring computer. For example, hexadecimal is used because it is the machine language of the computer

and is, therefore, very useful for rapid communication between the encoder and the controlling computer. BCD is a decimal digit that is expressed in natural binary code. This means that the next most significant bit in the next most significant byte will be incremented after every ten counts. This property is important because BCD can serve as a software link between the binary based output of an encoder and the decimal based counters which are common on some NC computers (Olesten, 1970, pp. 290-294).

Gray code and XS3 are two of only a few confident codes that can be used in encoders. The reason for this is that for every incremental movement, the bit pattern indirectly shifts toward the least significant bit. This is the opposite of BCD. This means that the danger of confusing a most significant bit is greatly reduced. It also means that any error is limited to the width of the increment.'

Positional sensors can be categorized into two types. The first type, linear, is used to measure the distance between two objects as they move along a straight line path. An everyday example of this would be the vernier calipers used in laboratories or machine shops. The second type, rotary, is used to measure the rotational distance between two objects as they move in a circular path. An everyday example of this would be the graduated circle on the dial of a combination lock. Since most machine tools have rotary moving parts and are also

connected to digital computers, logic suggests that a further study of rotary encoders would be most beneficial to improve positional positioning.

The choice of which model of digital encoder to use is dependent on the characteristics of the job and the environment that the job exists. The first job characteristic has at least two major factors. The first factor, positional resolution, indicates the smallest acceptable division of a unit of measure. Its applications vary from a high resolution use, such as the fitting of a piston into a cylinder, to a low resolution use, such as the pulling of a casting from a die. The second factor, movement reliability or movement repeatability, indicates the average maximum amount of error that will occur with repeated movements. Its applications vary from a highly repeatable use, such as the spot welding of parts on an assembly line, to a low repeatability use, such as the milling of a part in a tool and die shop.

The second characteristic of an encoder's usefulness, environmental effects, has two components. The first component, electrical interference, occurs when there are many inductive loads (motors, high current switches, etc.) near the encoder's circuit. A simple cure for this is to add filters and shielding to the encoder's power and receiving wires. However, in high resolution applications there may still be a problem because any electrical 'noise' that leaks past the shielding may have the same characteristics as the encoder's signal.

The second environmental component, the working space, has the greatest impact. The major problems with it are two fold. The first,

seal leakage, occurs when atmospheric contaminants, such as moisture or dust, leak past the shaft seal and wear away internal parts. The second problem, temperature control, occurs when great temperature changes, such as those found in a foundry, cause misalignment of parts through thermal expansion.

In view of these design parameters, two types of encoders are available in two different types of measurement configurations. The two configurations, absolute and incremental, refer to the shaft's position with respect to a reference position. The first one, absolute, compares itself to a fixed position in space through the use of a binary code. The code, in turn, consists of a graphical pattern of concentric rings and radial lines which are superimposed on each other (Fig. B.1, Appendix B). In other words, each radial sector is assigned a unique value by determining which ring in it is darkened or not.

The second measurement configuration, incremental, compares itself to a value that is stored in memory (see Fig. B.2, Appendix B). It, too, uses a binary code that consists of rings and sectors, except that the rings is limited to two (Critchlow, 1985, p. 127). This means that each increment is not given a unique pattern, since there are more increments than there are unique values for the binary code. Therefore, a position is assumed to exist based on the number of increments that were counted since the last movement.

The true test between the two concepts occurs after a given machine is accidentally turned off. When it is turned back on, the computer can sense an absolute encoder and know exactly where the shaft is



positioned. If an incremental encoder is sensed, the computer will have a false reading, since it does not have a previous value to compare against. Instead, the computer will assume that the present position is the new reference and will make future movements based on it.

The first of the two types of encoders, known as optical, are the most accurate and durable. To begin with, either an absolute or incremental binary code is photographically placed on a clear disk which is in turn mounted on a shaft. This subassembly, along with various photodetectors, are placed in a final housing. Since optical encoders are relatively immune to electrical interference, they are ideal for many situations. The major problem with them is precision. If a very small increment is needed, then only a very high quality photo engraving system can make them. This leads to a large initial cost.

The second type of encoder, electrical, has three subgroups. The first, frictional or tip, is similar to an optical encoder. Instead of using a clear disk and photodetector, a charged metal disk and contacting brushes are used. Whereas before a darkened spot blocked out light to a photodetector, a non-conducting 'spot' is now used to block out a electric current to the brush. In reality, this type of encoder is not much different than the slip rings on an ac motor. Since it is so similar, it suffers from the wear problem associated with slip rings. However, if the application requires low resolution and low repeatability, and a low price, a frictional encoder may be the preferred choice.

The second subgroup of electrical encoders, resistive, is similar in principle to a rheostat, potentiometer, or variable resistor. Basically, a wiper, similar to the brush in the previous example, contacts a loop or coil of electrically resistive material. As the shaft turns, the wiper moves along the coil, thereby changing the resistance of the encoder circuit. In this way, a resistive encoder is good because it theoretically has infinite resolution on an absolute scale. The main problem with it though, is the contact between the wiper and wire will wear down with time and will eventually give inaccurate readings.

The last subgroup of electrical encoders, inductive, is the most difficult to envision. The best way to envision one of these devices, sometimes known as a resolver, is to imagine an electrical transformer in which the secondary winding is free to rotate (Brite and Fioranelli, 1967a). When the primary winding is activated by an alternating current and the secondary winding begins to turn, a phase shift occurs in the secondary winding.

This phase shift creates a change in the voltage which is detected by the components in a servomechanism. Based on the polarity of the signal and the magnitude of the voltage, the servomechanism then turns in order to compensate for the movement. The problem with this encoder is that it is a precision electrical analog device and is therefore somewhat complex to build and calibrate for a given application. This

explains why they are very expensive to use. To get a better idea of how it works, Brite and Fioranelli (1967b) and Johnson (1966) offer the simplest explanation.

All of the previous types of encoders have used either light, resistance, reactance, voltage, or frequency to convey electrical information to a computer. However, there is one other property of electricity that no encoder has used yet. This property is capacitance. The reason why it has not been used is because of its sensitivity to its environment.

For decades, electrical engineers have known that whatever affects the insulating material between the conducting plates greatly affects the value of the capacitor. This effect was greatly noticed on the old air plate capacitors that were used in shortwave sets. Until crystal oscillators were available, a lot of time was spent trying to retune a station after it had been found. The reason was the heat of the set itself was changing the density of the air in the capacitor and was also changing the dimensions of the plates in the capacitor.

Despite these handicaps, recent uses for capacitive positioning have been found at the end of arm tooling on robotic manipulators and in shaft encoders. The robotic sensor can detect movement at 40 inches per second within a 12-inch radius. It does this by compensating for atmospheric conditions 500 times per second (Jablonowski, 1984).

The shaft encoder can measure up to 200 divisions per revolution by reducing environmental influences. This is done by coating a non-

conductive material in a geometric pattern on the plates and by reducing the air gap to a range between 0.005 and 0.05 inches (Williams, 1981).

The latter case demonstrates that most of the needs of an encoder are met by using a variable air plate capacitor. For example, many commercial capacitors sell for less than \$60.00 and in theory can yield a frequency resolution equivalent to 1/40,000 of a revolution. In addition, they are comparatively lightweight, simple in construction, reusable after an overvoltage accident, and are immune to contact wear.

This is possible since there are no parts contacting each other. The only problem, is to control its environment. This can be done by enclosing the capacitor and providing controlled air to it by a compressed air source.

### **Problem of the Study**

The problem of the study was to examine the possibility of using a microprocessor controlled, variable air gap plate capacitor as a means of accurately measuring the angular position of a shaft.

### **Purpose of the Study**

The purposes of the study are:

1. To determine if there was a predictable relationship between atmospheric humidity and the capacitive value of an air plate capacitor.
2. To determine if there was a predictable relationship between wet bulb and dry bulb temperatures and the capacitive value of an air plate capacitor.

3. To determine if a variable air plate capacitor could be used to accurately and repeatably position a shaft.

### **Need for the Study**

The need for the study was based on three problems. The first was there are two conflicting statements in the literature. The first author stated that "These (capacitive positional sensors) are suitable for the precise measurement of very small movements" (Lhote et al., 1984, p. 294). The second author stated that "Capacitive transducers . . . are not generally useful for robotic applications because of the variations in ambient conditions" (Critchlow, 1985, p. 138). These two quotes obviously disagree with each other.

The second problem was the cost versus precision of a given encoder was relatively high. This statement was based on a simple search of encoder advertisements. Their precision can vary from less than one division per revolution to at least 188,000 divisions per revolution (Modern equipment, 1984). Their costs can, vary from \$188.00 to over \$900.00, respectively. To put this in perspective, a vernier caliper with 0.01 inch accuracy will cost less than \$50.00 and a 1 inch micrometer will cost less than \$100. Therefore, if a computer-monitored sensor is preferred over its human counterpart and is more expensive than its human counterpart, then it is logical to try and reduce the cost of an encoder.

The last problem was that there was little information about using a digital computer to monitor the position of an air plate capacitor. This statement was the logical result of two divergent sources. The



first was that a hardware control loop which uses variable capacitors has been created (Jones, 1965). The second source was that a capacitive encoder has been tested (Williams, 1981). When one also takes into account that a control system must be devised to match any user's need, it makes sense that software should be used to join these two concepts in order to satisfy that need.

### **Assumptions of the Study**

1. For a given value and configuration, all variable air plate capacitors had the same electrical characteristics.
2. The air pressure was of standard consistency, was at 14.7 psia and was identical to the air found in factory settings and in both of the repeatability and environmental experiments.
3. The temperatures and humidities found in the environmental and repeatability experiments were similar to those found in a factory environment.
4. The types of capacitors examined in the study can be used in a factory environment.
5. The types of capacitors examined in the study were readily available to factory users.
6. The motor used in the repeatability experiment turns at a constant rate.
7. The air plate capacitors were manufactured such that the capacitance varies linearly as the capacitor turns.
8. All visual measurements were accurate.

9. All mirrored surfaces were flat and reflective.
10. The repeatability chamber isolates the atmosphere inside it from the humidity effects of the outside world.

### **Objectives of the Study**

The objectives of the study were to answer the following questions:

Was there a directly proportional relationship between the effects of temperature, humidity, and the capacitance of a variable air plate capacitor?

Could a variable air plate capacitor be used to position a turntable to within 3 degrees of error?

For a given wet and dry bulb temperature, was there a direct relationship between the rotation of a variable air plate capacitor and its capacitance?

### **Limitations of the Study**

1. The smallest time interval was as large as the smallest time interval available through a VIC 20 microprocessor.
2. The site for the repeatability experiment was limited to the east mow of the Department of Industrial Education and Technology's Building II.
3. The site for the environmental chamber experiment was limited to the electronic lab of the Department of Industrial Education and Technology.

4. All equipment was limited to those found at Iowa State University.
5. Measurement of fluid capacity was limited to measurement by volume, not by weight.
6. The environment in which each experiment takes place was limited only to the local conditions found in the mow for the repeatability experiment and in the electronics lab for the environmental chamber experiment.
7. The repeatability experiment had to be completed before August 1 to avoid the excessive temperature and humidities found in the mow.
8. The repeatability experiment had to be completed before August 27 in order to avoid the beginning of classes.

### **Hypotheses of the Study**

#### **Research Hypothesis I**

It was hypothesized that there was no linear relationship between software capacitance and the rotational position of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: \text{ANG} <> k_0 + k_1 * CP$$

$$H_a: \text{ANG} = k_0 + k_1 * CP$$



where ANG = angle of rotation

k0 = regression intercept

k1 = slope of regression line

CP = software capacitance

### **Research Hypothesis II**

It was hypothesized that there was no linear relationship between software measured capacitance and real capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

Ho:  $PF \neq k0 + k1 * CP$

Ha:  $PF = k0 + k1 * CP$

where PF = real capacitance

k0 = regression intercept

k1 = slope of regression line

CP = software capacitance

### **Research Hypothesis III**

It was hypothesized that daily environmental changes do not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

Ho:  $CP = Co + (Dir)i + (H1)j + (Po)k$

Ha:  $CP = Co + (Dir)i + (H1)j + (Po)k + (Day)l$

where

$C_o$  = intercept

$(Dir)_i$  = the direction indicator

$i = 1, 2$ ; where 1 = forward, 2 = reverse

$(H_1)_j$  = the relative humidity indicator

$j = 1, 2, 3, 4$ ; where 1, . . . , 4 was the position indicator

$(P_o)_k$  = the position; where  $k = 1, 2, 3, 4$

$(Day)_l$  = the day's indicator;  $l = 1, 2, 3, . . . , 12$

#### **Research Hypothesis IV**

It was hypothesized that the direction of rotation does not affect the rotational position of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$H_o: CP = F_o + (H_1)_i + (P_o)_j$

$H_a: CP = F_o + (H_1)_i + (P_o)_j + (Dir)_k$

where

$F_o$  = intercept

#### **Research Hypothesis V**

It was hypothesized that wet bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$H_o: CP = G_o + (Dir)_i + (P_o)_j$

$H_a: CP = G_o + (Dir)_i + (P_o)_j + (q_o * W_b)$

where

$G_o$  = intercept

$q_o$  = slope of regression line

$W_b$  = wet bulb temperature

### **Research Hypothesis VI**

It was hypothesized that dry bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$H_o: CP = Mo + (Dir)i + (Po)j$

$H_a: CP = Mo + (Dir)i + (Po)j + (p*Db)$

where

$Mo$  = intercept

$p$  = slope of regression line

$Db$  = dry bulb temperature

### **Research Hypothesis VII**

It was hypothesized that both wet bulb and dry bulb temperatures do not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$H_o: CP = Mo + (Dir)i + (Po)j$

$H_a: CP = Mo + (Dir)i + (Po)j + (q_o*W_b) + (p*Db)$

**Research Hypothesis VIII**

It was hypothesized that an unenclosed variable air plate capacitor can not be used to position a shaft to within 3 degrees of error.

Statistical Research Hypothesis:

$$H_0: u \geq 3.0$$

$$H_a: u > 3.0$$

where  $u$  = angular error between the target value and the actual value

**Research Hypothesis IX**

It was hypothesized that relative humidity does not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: Q_{h11} \neq Q_{h13}$$

$$H_a: Q_{h11} = Q_{h13}$$

where  $Q_{h11}$  = capacitance of vented capacitor

$Q_{h13}$  = capacitance of unenclosed capacitor

**Research Hypothesis X**

It was hypothesized that relative humidity does not affect the capacitance of an enclosed but unventilated variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: Q_{h11} \neq Q_{h13}$$

$$H_a: Q_{h11} = Q_{h13}$$

where  $Q_{h11}$  = capacitance of vented capacitor

$Q_{h13}$  = capacitance of unenclosed capacitor

There was no decision for either hypothesis since the capacitor under study was defective.

### **Research Hypothesis XI**

It was hypothesized that relative humidity does not affect the capacitance of an enclosed and vented variable air plate capacitor.

Statistical Research Hypothesis:

$H_0: Q_{h11} < > Q_{h13}$

$H_a: Q_{h11} = Q_{h13}$

where  $Q_{h11}$  = capacitance of vented capacitor

$Q_{h13}$  = capacitance of unenclosed capacitor

### **Definition of Terms**

Accuracy- See Resolution.

Backlash- The relative motion of loose mechanical parts which occurs between two consecutive and opposite directions of travel.

BCD (Binary Coded Decimal)- A four bit binary code which represents a decimal digit in binary form.

Binary- A numbering system which has 2 as its base.

Binary digit- A digit which has only two values: either 1 or 2.

Binary word- A group of binary digits. The group number is dependent on the microprocessor using it. The number is usually 8, 12, 16, or 32 bits.

Bit- See Binary digit.

Bit shifting- The movement of the bit pattern in a binary word to overflow into a carry bit.

Byte- See Binary word.

CNC (Computer Numerically Control)- The use of a computer and a higher level computer language to convert numeric data, or movement descriptions, into machine tool movement.

Dewpoint- The temperature at which atmospheric water vapor begins to condense when cooled without changing the atmospheric pressure.

Dry bulb temperature- The actual temperature as measured by a dry bulb thermometer.

Encoder- A transducer which converts positional information into a unique electronic representation.

Gray code- A binary code in which each change in an increment shifts any bit down to the least significant bit.

Hexadecimal- A four bit binary code in which the base is 16 and each digit is represented by a natural binary value.

Machine language- A software language which directly controls hardware circuitry.

NC (Numerical Control)- The use of a computer and punched tape to direct machine tool movement.

Positional sensor- A device used to determine position with respect to reference frame. See Encoder.

Real capacitance- Capacitance which is measured by a capacitance meter.

Relative humidity- The ratio between the actual water pressure and the

saturation water pressure.

Repeatability- The ability of a machine tool to return to a previous position under the same operating conditions with the smallest amount of error as possible.

Resolution- The smallest increment that is discernible by a positional sensor.

Resolver- A type of encoder which uses the change in an electromagnetic field as the basis for position sensing.

Robot- A reprogrammable (by software), multifunctional manipulator designed to move material parts, material, or specialized devices through variable programmed motions for the performance of a variety of tasks.

Sensor- Any type of transducer.

Shifting- See bit shifting.

Software capacitance- Capacitance as sensed by a microprocessor and reported through software output.

Wet bulb temperature- The temperature at which atmospheric air is cooled by the evaporation of water liquid into water vapor at constant pressure.



## CHAPTER II. LITERATURE REVIEW

The review of literature began by asking faculty members of the department of Industrial Education and Technology about the use of air plate capacitors in positional sensing. The results of this discussion were 1) capacitors tend to 'drift' or change their values greatly as their environment changes, and 2) technical data regarding these effects were not readily available due to changes in radio technology.

The information search began by using the Compuserve computer search service at the William Robert Parks and Ellen Sorge Parks Library. Since these data only have citations dating back to January 1, 1976, only 30,000 initial periodical citations were found. From this list only one had the topics of capacitors and positional sensing. This citation was noted but not accepted, since it dealt with using a capacitive field as a safety field which protected human workers (Jablonowski, 1984). Therefore, the search continued by examining literature sources before 1976.

The results of this search were more encouraging. The four sources which were uncovered suggest answers to the basic questions of the study, but their value was in doubt. The first citation was a group of temperature and humidity nomographs for variable air plate capacitors (Dummer, 1957, pp. 49, 75, 90). Since it was almost thirty years old, it was cautiously accepted. The second citation contains an equation and a nomograph for the effect of humidity on high frequency microwave cavities (Westman, 1970). Since a variable air plate capacitor that is



used in a high frequency circuit is technically a resonant cavity, this source was also accepted with some reservation.

The third citation was the only one that used a capacitor as a rotational sensor in an electromechanical control system (Jones, 1965, p. 328). The capacitor was used as a balancing arm for a chart recorder. The fourth citation mentions using a modified variable air plate capacitor to detect the phase shift of a high frequency circuit (Williams, 1981). This article, too, was rejected since the capacitor in question had an air gap which was much narrower than those which are commercially available and was not available on a commercial scale.

The fifth citation almost exactly matched the problem statement of this study. Vanwesi and Trivedi (1975) wanted to use variable air plate capacitors as a remote sensing device for monitoring the status of oil pipeline valves. Their study was somewhat thorough, but was also unclear in two areas. The first area was that a frictional reducing pulley was used to increase the rotation of the input shaft from 180 to 360 degrees. This idea was notable, but it was also subject to error, since a belt can slip in the groove of a pulley. The second area was the environment in the capacitor was uncontrolled. This may account for the one percent error readings they conveyed in their report.

### CHAPTER III. METHODOLOGY OF THE STUDY

The methodology of the study consisted of designing and building the equipment needed to do two experiments. The first experiment, a software controlled positional repeatability experiment, used a procedure similar to ASTM F-801 83 (Genco and Task, 1985). Its purpose was to measure the positional repeatability of a capacitor transducer by using a reflected laser beam to measure positional error.

The purpose of the second experiment was to determine how humidity affects capacitance. It was similar to the psychrometer calibration used at Iowa State's Research Equipment Assistance Program (REAP). The only change in REAP's procedure was that the psychrometer was replaced by an unenclosed capacitor, an enclosed but unventilated capacitor, and an enclosed but ventilated capacitor.

#### Theory of Construction for the Repeatability Experiment Apparatus

##### Construction of the capacitor test frame

The ultimate goal of the frame was to measure small angular changes of a light beam over a relatively long distance. However, environmental vibrations can also create angular changes in a light beam. Therefore, something must absorb these outside vibrations before they reach any mirrored surface.

The method used to do this was to mount all moving parts on an aluminum box, which in turn was bolted onto a wooden frame that was filled with concrete blocks (Figs. C.2-C.4, Appendix C). The theory behind this was that the wood would absorb the energy from small

vibrations while the opposing inertia of the concrete blocks would absorb somewhat larger vibrations. Any remaining vibration would be dampened by the aluminum box, since it was isolated from the frame. In addition, the aluminum box acts like a removable module that aids in moving parts during the construction of the frame.

#### Construction of the mirror alignment system

The purpose of the mirror alignment system was to use a laser light beam to reflect off of a mirror mounted on a shaft coupling, then to reflect off of one of four fine adjustment mirrors and then to reflect off of a collection mirror on to a wall size grid (Figs. C.6-C.9, Appendix C). By varying the distances between the three groups of reflecting surfaces, many different angular widths were investigated.

#### Construction of the motor control and computer interface

The purpose of the motor control and interface was to change the sequential position of the motor based on the capacitance value of the sensor and the computer's software controlled output signal. The input capacitance/signal was processed by using it in an RC network of an LM 555 oscillator circuit. The output frequency was sampled in a hardware counting circuit over constant periods of time. At the end of each sample, the VIC 20 monitored the binary code of the sample through its parallel user port, processed it, and decided whether to turn the motor on or off.

The output signal of the computer, as communicated through its output port, was sent to 120 volt, single pole, single throw (SPST) relay (Figs. C.5 and C.13, Appendix C). The relay, in turn, activates the motor. The equipment used in the repeatability experiment was:

- a gang type variable air plate capacitor.
- a motor control/interface between the computer capacitor, and motor.
- a two phase, reversible, low speed ac motor.
- a 95 milliwatt, class I, ruby red, gas laser.
- a mirror alignment system including four fine adjustment mirrors, one wide collecting mirror, and a wall sized measurement grid.
- two desks, electrical power connections, and miscellaneous fixtures to hold all of the components.
- a 20 inch box type floor fan.
- a sling psychrometer.

### Procedure for the Repeatability Experiment

#### Build moving parts module

- Obtain aluminum, 1 1/2 inch diameter delrin rod, wooden boards, plywood sheet, motor/gear reducer, and capacitor.
- Drill shaft and set screw holes in the coupling.
- Mill a flat on the motor coupling.
- Build aluminum box.
- Layout components on the outside of the box and mark drill holes.
- Drill holes, remove flash, and bolt down components.
- Test the system to see if any shaft binds as it rotates.

**Build test frame**

- Measure and cut pieces to fit around aluminum box.
- Starting with the base, mount each piece individually until the board members are assembled.
- Bolt the box onto the frame and lean the plywood sheets on the frame to see how the frame will look. Add shims if necessary.
- Remove aluminum box. Glue and nail plywood boards to the board frame.
- After drying, scrape off excess glue, and sand down edges.
- Remount box and test for successful operation.

**Setup equipment**

- Move all components to the east mow of Industrial Education and Technology II.
- Move desks on the south side of the mow and place the fine adjustment mirrors on one of them.
- Place the test frame on an steel I-beam.
- Place grid paper on the mow's south wall.
- Place the collecting mirror on a desk at least 150 feet north of the test stand.
- Place the laser near the mirror on the coupling so that as the motor turns, the beam reflects off of it and onto the fine adjustment mirrors, then to the collecting mirror, and finally on to the grid located on the mow's south wall.
- Repeat the previous process until the beam's spot fits onto the grid.

**Develop sensing and motor control interfaces**

- Build LM 555 timer and motor control interfaces. The LM 555 timer interface was adopted from "The 555 Timer as a Pulse Generator" article from Mullen's lab manual (1985). The motor control was adapted from "Parts Sorting System" by Kim and Baack (1985). The result of connecting these circuits together is shown in the schematic of Fig. C.13 in Appendix C.
- Test each and connect the components to the shaft capacitor.
- Load and run the machine language program "MLTIMER" from the "Measuring Time with a VIC 20" article in Mullen's lab manual (1985). A hard copy of it is in Fig. E.1, Appendix E.
- Load BASIC program "TLAB8" and run it (Fig. E.2, Appendix E).
- Rotate the coupling mirror from the first angular position through to the fourth angular position and record average time readings for each position.
- Re-align fine adjustment mirrors if necessary to assure a large enough numerical difference between positions.

**Develop monitoring software**

- Write a program which records the following variables for each position:
  1. Wet bulb temperature.
  2. Dry bulb temperature.
  3. Day of recording.
  4. Distances for the top, bottom, left side, and right side of light spot on the grid.

5. The program should also save the data to a disk, create a hard copy of the data, and also be able to edit the previous group of data in the event of a keypunching error.

- Perform enough trial runs of the program with the equipment such that the program was debugged.
- Assuming that the results of the debugging step are statistically significant, perform an actual field test of at least 35 samples. Repeat this step until the results are statistically significant.

#### **Perform the experiment**

- Turn on the power.
- Prepare the psychrometer.

Fill the psychrometer and moisten its wet bulb wick. Hang the psychrometer over the top of the fan with the thermometers on the windward side. It should be dangling approximately seven inches from the left edge of the fan, with the wet bulb facing into the wind. Turn the fan on.

- Prepare experimental equipment. Adjust manual motor control switch and manual override switch to begin rotation at the zero position in the counter-clockwise direction.
- Perform a sampling run. Choose a position and obtain the date, wet bulb temperature, dry bulb temperature, and the left, right, top, and bottom dimensions of the spot. Repeat this step for all four positions.



- Reverse the direction and data for four more positions.
- Continue the forward and reverse sampling cycles for a total of five times.

### **Theory of Construction for the Environmental Chamber Apparatus**

The purpose of the environmental chamber was to determine how three different environmental humidities affect unprotected, protected but not ventilated, and protected but ventilated capacitors. To do this though, a chamber was used to provide a space where environmental conditions are held constant.

The control of humidity was established by placing a container filled with a water-based solution in the chamber. If left alone, a part of the water would evaporate until a chemical equilibrium was established inside the chamber. This equilibrium was based on its vapor pressure and temperature. If the solution used was pure water, the relative humidity would be 100 percent inside the chamber.

When a second substance is added to saturation in the pure water solution, the humidity stabilizes at a new level. This phenomenon is based on the chemical equilibrium concept of saturated solutions. For a more thorough explanation of the theory, the reader is invited to read Levine (1978, pp. 200-218, 290-300) or any other physical chemistry text. The choice of which substances to use came from a list which appears in the Handbook of Chemistry and Physics (Weast, 1986, p. E-42) under the topic of Constant Humidity.

The relationship between the capacitors and atmospheric humidity can be modeled by using the chamber as if it were the assembly room of a



factory. Therefore, it would be logical to determine what affect the chamber's atmosphere has on a protected capacitor, an unprotected capacitor, and a capacitor whose humidity is controlled through filtering agents. The equipment used to do the environmental chamber experiment was:

- a recycled chart recorder box.
- a small recycled air circulation fan.
- three 180 degree, gang type air plate capacitors.
- two sealed plastic containers.
- one aquarium air pump.
- four glass containers containing four different hygroscopic salts.
- two 100 degree F Mercury thermometers.
- one emptied pill container.
- one fiber wick.
- one air pump desiccator.

#### **Procedure for the Environmental Chamber Experiment**

##### **Modification of the chart recorder box**

- Obtain components and other materials.
- Remove internal mechanisms (motors, platen, paper feed drive, etc).
- Clean interior and exterior surfaces with window cleaner.
- Mount circulating fan on the upper center of the back wall.
- Place ceramic dish on the bottom of the chamber.

**Build support fixture and capacitor enclosures**

- Cut a 3/8 inch plexiglass sheet into three pieces:
  - one at frame size (12 inch X 24 inch)
  - two at dish height (approximately 2.5 inch X 15 inch)
- Bend the two longer pieces to create support legs. Drill #7 ventilation holes in them.
- Place a capacitor and two of the containers on the larger sheet at approximately 6 inch centers.
- Mark off tentative positions.
- Drill two, #59 holes in the containers for connecting wire.
- Drill #7 ventilation holes in the proper container.
- Insert aquarium adapters into the containers and seal them with glue.

**Build wet bulb housing**

- Obtain a 4 inch long, 1.25 inch diameter pill container and wash it.
- File a hole with a 3/8 inch round file near the closed end of the container. Remove flash.
- Cut a piece of wick fiber and insert in the hole to determine if it fits.
- Cement the lid on the container. Seal with wax if necessary.
- Fill with water to determine if the container leaks.
- Obtain a 1.5 inch wide strap of scrap aluminum (26 gauge) that is long enough to wrap around the container at least once.

- After wrapping the coil snugly around the container, hold the coil and push the container out.
- Drill a #7 hole through the coil and rivet it to the rest of the strap in order to prevent unraveling of the coil.
- Mount wet bulb housing such that little wick area is exposed and that it is the furthest thermometer from the fan.

#### Modify outer shell

- Drill two holes in the top of the box with a 27/32 inch drill.
- Drill a 1/4 inch hole in two #5 rubber stoppers for the thermometers.
- Paint the inside of the shell with paint primer.
- Mount thermometer and wet bulb housings.
- Seal glass around the door with silicone caulk.

#### Assemble drying filter

- Obtain a wide mouth 500 ml Erlenmeyer flask, 800 cc of calcium chloride ( $\text{CaCl}_2$ ), 20 inches of 4 mm glass tubing and a #13 rubber stopper.
- Drill four #10 holes in the stopper.
- Cut four, 5 inch lengths of tubing and flame both ends of each.
- Apply a coating of petroleum jelly around each tube and insert it through the stopper such that 2 inch of tubing protrude on both sides of the stopper.
- Mix approximately 5 cc of Dri-rite with 350 cc of  $\text{CaCl}_2$  and STORE IN AN AIRTIGHT CONTAINER until needed.

**Setup equipment**

- Move all the components to the electronics lab of Industrial Education and Technology Building II.
- Connect all components, including an empty drying filter, to determine if they are compatible with each other.
- Insert vent tubes through a hole in the chamber wall along with the sensing wires.
- Connect tubes to the pump and containers.
- Insert wires through the top of each container.
- Solder the required connections to all capacitors.
- Tape all holes in the outer shell.
- Trowel auto body molding around telephone wires and the ventilation tubing to thoroughly seal up the chamber.
- Snugly insert thermometers into shell.
- Turn on air pump and fan. Close the door and check exhaust on the air filter to determine if there is sufficient air pressure in the system.

**Build sensing interface**

- Assemble 3 LM 555 oscillator circuits and connect them to the output port of a VIC 20 microprocessor (see Fig. D.15 in Appendix D).
- Load machine language program "MLTIMER" and run it.
- Load BASIC program "TLAB8" and run it for each circuit.
- Test the interface with the three capacitors under study.

**Develop monitoring software**

- Based on these, positions write a program which records the following variables for each position:
  1. Wet bulb temperature.
  2. Dry bulb temperature.
  3. The capacitance for a given position on all three capacitors.
- The program should also stop periodically to revise the dry and wet bulb temperatures.
- The program should also save the data to a disk and create a hard copy of the data.
- Perform enough trial runs of the program with the equipment such that the program was debugged.
- Assuming that the results of the debugging step are statistically significant, perform an actual field test of at least 35 samples. Repeat this step until the results are statistically significant.

**Perform the experiment**

1. Prepare the salt.

Dry 350 cc of each salt at 250 degrees F for at least four hours.

Let them cool to ambient temperature in a desiccator.

2. Prepare the chamber.

Turn on electronic components.

Change the desiccant for the controlled atmosphere capacitor if needed. Be sure that all plastic tubes are tightly affixed

to the glass tubing and that the stopper is tightly inserted in the flask.

Thoroughly mix 100 cc of deionized water to each salt.

Fill the wet bulb thermometer reservoir as needed.

3. Choose a shaft position for each capacitor.

For every capacitor:

Measure the software capacitance value.

Measure the real capacitance value with an LC meter.

Close the covers on the capacitors.

Perform a sample run for a given humidity level.

a. Stabilize the chamber.

Insert the salt solution into the chamber.

Close the chamber door.

Turn on the air pump and fan.

Wait for one hour for equilibrium to be established.

b. Obtain data.

Obtain 100 samples.

Wait for the end of the first two minute interval.

Beginning with the first capacitor, average 30 observations.

Store the average in memory.

Average and store data for the other two capacitors.



Print out sample number, absolute time, the three capacitance values, position number, and humidity level.

Wait for the next two-minute interval to begin.

After every four samples, record the wet bulb and dry bulb temperature.

c. Repeat a and b for the other two humidity salts.

4. Repeat step 3 for the other two positions.

### **Method of Data Analysis**

#### **Relative humidity determination**

The procedure used to calculate relative humidity was derived from Chapter 4 (pp. 110-112), Chapter 5 (pp. 137, 141) and Chapter 11 (pp. 390-405) of Fellingner and Cook (1985). The data for the properties of water came from Keenen et al. (1969). The program used to process the data is in Fig. E.6 of Appendix E. The steps needed to find the relative humidity are:

1. Find the humidity ratio at the wet bulb temperature (W2):

$$W2 = .622 * (MP2 / (AP - MP2)),$$

where

MP2 = water vapor pressure (psi) at the wet bulb temperature  
(degrees F),

AP = atmospheric pressure (psi),

.622 = molecular weight of water/molecular weight of standard  
air

$$= 18/28.966.$$

2. Find the humidity ratio of the atmosphere ( $W_1$ ):

$$W_1 = ((W_2 * H_{M2}) - 0.24 * (DB - WB)) / (H_G - H_{F2}),$$

where

$H_{M2}$  = enthalpy (Btu/lbm) of a liquid/vapor mixture at the dry bulb temperature,

$H_G$  = enthalpy of the gaseous phase of water at the dry bulb temperature,

$DB$  = dry bulb temperature

$WB$  = wet bulb temperature

0.24 = enthalpy of dry air (Btu/lbm of standard air)

$H_{F2}$  = the enthalpy of liquid water at the wet bulb temperature.

3. Find the partial pressure of water vapor in the air ( $p_w$ ):

$$p_w = (W_1 / .622 * AP) / (1 + W_1 / K)$$

where  $K = .622$  (see constant above).

4. Find the relative humidity ( $RH$ ):

$$RH = P_w / DP_1,$$

where  $DP_1$  = liquid pressure at the dry bulb temperature.

### Conversion from software capacitance to angular spread

The conversion from software capacitance to angular spread was done with the simple linear regression model which was tested in Hypothesis I.

The equation was

$$\text{ANG} = (.21326005 * \text{CP}) + 170.2991429$$

where

ANG = absolute measurement of the angle in degrees,

CP = software capacitance.

## CHAPTER IV. FINDINGS OF THE STUDY

The processed results of this study are displayed in this chapter as two parts. The first part states the general statistical summary for both experiments. The trends inferred from this summary help explain the formal statistical tests which follow in the second part. The second part contains various rigorous statistical tests.

### Overall Statistical Summary

#### Repeatability experiment

Twelve sampling runs were performed at 5:45 a.m. between July 14 and August 4 (see Appendix C). Each run consisted of 10 rotations and each rotation had four positions. Each run took approximately 90 minutes to complete. On the third day of sampling, it was noticed that the stopping point for each position tended to fall either at the beginning or ending of the beam path on the grid. In other words, the data seemed to be bi-modally distributed. Therefore, the direction of rotation was recorded thereafter.

Out of 550 observations, 120 were missing values due to the lack of recording a direction of rotation. Out of these 120, 15 were out of range. The temperature ranged from 75 to 88 degrees F and the relative humidity ranged from 44 to 69 percent. The valid data summary is in Table 2.

Table 2. Valid Data Summary for Repeatability Experiment

	Capacitor Position			
	1	2	3	4
<u>Reverse</u>				
No. of Observations	34	44	55	56
Position Mean <sup>a</sup>	-19.87	-41.70	-28.20	-30.07
Std. Deviation	13.22	12.10	9.65	10.06
Capacitance Mean <sup>b</sup>	517.67	481.39	432.68	325.25
Std. Deviation	3.86	2.37	1.49	2.35
Angular Mean <sup>c</sup>	59.90	67.63	78.02	100.94
Std. Deviation	0.61	0.51	0.32	0.50
Angular Error Mean	1.05	1.04	1.14	1.08
Std. Deviation	0.35	0.37	0.32	0.34
<u>Forward</u>				
No. of Observations	34	44	55	56
Position Mean	-10.81	-24.22	-10.07	-12.77
Std. Deviation	11.16	14.45	9.71	11.42
Capacitance Mean	525.51	490.27	441.85	334.06
Std. Deviation	3.81	3.35	3.68	3.39
Angular Mean	58.22	65.74	76.07	99.06
Std. Deviation	0.81	0.72	0.78	0.72
Angular Error Mean	1.02	1.12	1.06	1.06
Std. Deviation	0.39	0.27	0.39	0.37

<sup>a</sup>The position in inches on the reference grid.

<sup>b</sup>The capacitance in microseconds.

<sup>c</sup>The angle and angle error as measured in degrees.

**Environmental test experiment**

The environmental test experiment was performed between August 21 and August 24 (see Appendix D). All experiments were performed at 4:30 p.m. Two humidity levels were monitored with three positions within each level. Each position had 84 samples with 350 observations averaged per sample. Out of 504 samples, there were no missing values.

Individual capacitor data are shown in Table 3.

Table 3. Summary of Individual Capacitive Data for All Capacitors in the Environmental Experiment<sup>a</sup>

	Capacitor Label					
	C1		C2		C3	
	Capacitance <sup>b</sup>					
	Soft	Real	Soft	Real	Soft	Real
Position						
1	660	110	347	111	600	107
2	520	102	410	100	700	106
3	440	- <sup>c</sup>	560	- <sup>c</sup>	1000	- <sup>c</sup>

<sup>a</sup>The direction of rotation for each capacitor was: C1:clockwise; C2: counterclockwise; C3 clockwise.

<sup>b</sup>The software capacitance is measured in microseconds. The real capacitance is measured in picofarads.

<sup>c</sup>The real capacitance for position 3 is unavailable due to a malfunctioning meter.



There were no programming problems (Fig. E.5, Appendix E). Since there are not real capacitance values for position three, the data used for analysis were referenced from software values.

Unexpected events occurred during the analysis of the above data. Initially, the data were plotted to determine if inferences could be drawn from them (see Figs. D.1-D.6, Appendix D). Upon inspection, it appeared that C2 may have been defective, since it appeared to have a larger change in variance at each position cluster. Its clusters also appeared to have conflicting trends for each humidity level.

To determine if it was defective, 20 random samples were drawn from each 84 element data set. This was done to avoid replicating the original experiment. Next, the new data set was plotted and the mean and standard deviation were calculated. The plot was similar to the first one. The statistical results are in Table 4.

The means for capacitors 1 and 3 have a consistent trend for both humidity levels. The middle values for capacitor 2, however, deviate from the trend. The variances for capacitors 1 and 3 change within a 20 to 1 ratio between positions for all humidity levels. The variance for a low humidity in capacitor 2 changes in almost a 95 to 1 ratio. Along with the observation that the variance trends in capacitor 2 are greatly divergent from each other, these observations tend to support the proposition that capacitor 2 was defective.

Table 4. Summary of Mean and Standard Deviation Data for All  
Capacitors in the Environmental Experiment

Humidity	Capacitor Label					
	C1		C2		C3	
	High	Low	High	Low	High	Low
Mean (microseconds)						
Position						
1	747.88	483.58	420.89	568.50	620.26	599.43
2	1001.52	732.17	409.77	402.14	542.32	531.63
3	1332.64	1055.52	604.05	593.98	431.36	429.99
Variance (microseconds)						
Position						
1	98.22	219.29	139.21	4375.03	81.46	176.72
2	689.86	25.59	41.42	46.93	38.39	15.66
3	4153.24	500.97	851.58	341.50	104.00	44.36

### Analysis of the Research Hypotheses

Each research hypothesis will be examined statistically and will include a brief description. Unless otherwise noted, the statistical test used will be an "F" test or a confidence interval test. In each case, alpha has a value of 0.05. The methods used to do this were found in the General Linear Models (GLM) procedure in the SAS software

program. The reference values for the F test and Z scores were from the "Normal Probability Function" and "F Distribution Function" tables found in Beyer (1978, pp. 524, 530-543).

### Research Hypothesis I

It was hypothesized that there is not a linear relationship between software capacitance and the rotational position of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: ANG <> k_0 + k_1 * CP$$

$$H_a: ANG = k_0 + k_1 * CP$$

The regression equation from SAS was  $ANG = 170.29914297 + (-2.1326005 * CP)$  with an R-square of 0.993070. The standard error for  $k_0$  was 1.43614363 and the standard error for  $k_1$  was 0.00319965. To determine if this equation was a good estimator of the regression equation, the following hypotheses must be tested.

$$H_0: k_1 = 0$$

$$H_a: k_1 <> 0.$$

This can be determined in Table 5.

Table 5. F-test for Statistical Significance Between Software  
Capacitance and Angular Deviation

Source	df <sup>a</sup>	SS <sup>b</sup>	MS <sup>c</sup>	Fvalue <sup>d</sup>
Regression	1	20377.62	20377.62	4442.35
Error	31	142.20	4.5	
Total	32	20519.82		

<sup>a</sup>df= degrees of freedom.

<sup>b</sup>SS= sum of squares.

<sup>c</sup>MS= mean sum of squares.

<sup>d</sup>F value= The computed F statistic. Equal to  
 $MS_{\text{Regression}} / MS_{\text{Error}}$ .

With alpha = 0.05, the critical value of F (1,31) = 4.19. Since F value was greater than this, the null hypothesis of Research Hypothesis I can be rejected.

### **Research Hypothesis II**

It was hypothesized that there was no linear relationship between software measured capacitance and real capacitance of an unenclosed variable air plate capacitor.

## Statistical Research Hypothesis:

$$H_0: PF <> k_0 + k_1 * CP$$

$$H_a: PF = k_0 + k_1 * CP$$

The regression equation from SAS was  $PF = 44.83965023 + (0.28788795 * CP)$  with an R-square of .983656. The standard error for  $k_0$  was 2.99155049 and the standard error for  $k_1$  was 0.00666502. To determine if this equation was a good estimator of the regression equation, the following hypotheses must be tested.

$$H_0: k_1 = 0$$

$$H_a: k_1 <> 0.$$

This can be determined in Table 6.

With  $\alpha = 0.05$ , the critical value of  $F(1,31) = 4.19$ . Since  $F$  value was greater than this, the null hypothesis of Research Hypothesis II can be rejected.

**Research Hypothesis III**

It was hypothesized that daily environmental changes do not affect the capacitance of an unenclosed variable air plate capacitor.

Table 6. F-test for Statistical Significance Between Software  
Capacitance and Real Capacitance

Source	df	SS	MS	F value
Regression	1	37134.81	37134.81	1865.71
Error	31	617.02	19.90	
Total	32	37751.83		

Statistical Research Hypothesis:

$$H_0: CP = Co + (Dir)i + (Hl)j + (Po)k$$

$$H_a: CP = Co + (Dir)i + (Hl)j + (Po)k + (Day)l$$

The sum of squares for Day was 15.60606; its mean square error is 0.6221; its degree of freedom was 11. Therefore, F value was equal to  $(15.60606/11)/0.6221$  or 2.28. The R-square value was 0.998699. To determine if this relationship was significant, F value must be compared with  $F(11,292)$  which was 1.81. Since F value was greater than  $F(11,292)$ , the null hypothesis was rejected.

**Research Hypothesis IV**

It was hypothesized that the direction of rotation does not affect the rotational position of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: CP = Fo + (Hl)i + (Po)j$$

$$H_a: CP = Fo + (Hl)i + (Po)j + (Dir)k$$

The sum of squares for Dir was 456.895302; its mean square error was 0.65103295; its degree of freedom was 1. Therefore, F value is equal to  $(456.895302/1)/0.65103295$  or 701.8. The R-square value is 0.998587. To determine if this relationship was significant, F value must be compared with  $F(1,303)$  which was 3.84. Since F value is greater than  $F(1,303)$ , the null hypothesis was rejected.



**Research Hypothesis V**

It was hypothesized that wet bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: CP = G_0 + (Dir)i + (Po)j$$

$$H_a: CP = G_0 + (Dir)i + (Po)j + (q_0 * W_b)$$

The sum of squares for the wet bulb variable was 0.34259505, while the mean square error was 0.65766157. Therefore, F value was equal to  $0.34259505 / 0.65766157$  or 0.52. The R-square value was 0.998573. To determine if this relationship was significant, F value must be compared with  $F(1,307)$  which was 3.84. Since F value was less than  $F(1,307)$ , the null hypothesis was accepted.

**Research Hypothesis VI**

It was hypothesized that dry bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_0: CP = M_0 + (Dir)i + (Po)j$$

$$H_a: CP = M_0 + (Dir)i + (Po)j + (p * D_b)$$

The sum of squares for the dry bulb variable was 0.00493678, while the mean square error was 0.65877595. Therefore, F value was equal to  $0.00493678 / 0.65877595$  or 0.01. The R-square value was 0.998571. To determine if this relationship was significant, F value must be compared with  $F(1,303)$  which was 3.84. Since F value was less than  $F(1,307)$ , the null hypothesis was accepted.

**Research Hypothesis VII**

It was hypothesized that both wet bulb and dry bulb temperatures do not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

$$H_o: CP = Mo + (Dir)i + (Po)j$$

$$H_a: CP = Mo + (Dir)i + (Po)j + (qo * Wb) + (p * Db)$$

Since ANOVA is sensitive to the order of which variable was being processed, both combinations of variable order will be analyzed.

The sum of squares of dry bulb controlling for wet bulb was 2.43037962 while the mean square error was 0.65179164. Its degree of freedom was 1. Therefore, F value was equal to  $2.43037962 / 0.65179164$  or 3.73. The R-square value was 0.998590. To determine if this relationship was significant, F value must be compared with  $F(1,302)$  which was 3.84. Since F value was less than  $F(1,302)$ , the null hypothesis was accepted.

The sum of squares of wet bulb controlling for dry bulb was 2.76803789 while the mean square error was 0.65179164. Therefore, F value was equal to  $2.76803789 / 0.65179164$  or 4.25. The R-square value is 0.998590. To determine if this relationship was significant, F value must be compared with  $F(1,302)$  which was 3.84. Since F value is greater than  $F(1,302)$ , the null hypothesis was rejected. The discussion of this conflict will be discussed later.

### Research Hypothesis VIII

It was hypothesized that an unenclosed variable air plate capacitor can not be used to position a shaft to within 3 degrees of error.

Statistical Research Hypothesis:

$$H_0: u \geq 3.0$$

$$H_a: u < 3.0$$

The method of testing will be to use a Z score to determine if an error of three was within a 99.9 percent confidence interval. The mean angular error was 1.07582449; the standard deviation was 0.344777125; the number of samples was 309. The Z score for 99.9 percent was 3.33. The lower confidence value was  $1.07582449 - (3.33 * .344777125 / 17.578396) = 1.0105$ . The upper confidence limit was  $1.07582449 + (3.33 * .344777125 / 17.578396) = 1.1411$ . Since 3.00 was outside this range, the null hypothesis was rejected.

The next three hypotheses refer to Table 7. The concept behind testing them will be to group the capacitances as a whole and examine how it behaves as it covaries with respect to an individual capacitor, relative humidity, and position of rotation. This was logical, since the result of each hypothesis was to determine if relative humidity affects capacitance regardless of which rotational position or treatment was being investigated.

The important section to look at in the table was the area under the "CONTRAST" section. This section describes the relationship between capacitance and the following combinations: position, type of capacitor

Table 7. Anova Table for Environmental Experiment

GENERAL LINEAR MODELS PROCEDURE				
DEPENDENT VARIABLE: $Q^a$				
Source	DF	SUM OF SQUARES	MEAN SQUARE	
Model	11	14.63973833	1.33088530	
Error	108	0.08529385	0.00078976	
Corrected Total	119	14.72503218		
Source	DF	Sum of Squares	F VALUE	PR > $F^b$
C	1	8.19828923	10380.76	0.0001
HL	1	1.01169946	1281.02	0.0001
PO	2	0.25785351	163.25	0.0001
C*HL	1	0.52562798	665.56	0.0001
C*PO	2	4.54622684	2878.24	0.0001
HL*PO	2	0.06500378	41.15	0.0001
C*HL*PO <sup>c</sup>	2	0.03503754	22.18	0.0001
Contrast	DF	Sum of Squares	F VALUE	PR > F
PO Linear	1	0.46829929	592.97	0.0001
PO Quadratic	1	0.02788427	35.31	0.0001
C*PO Linear	1	4.52289779	5726.94	0.0001
C*PO Quadratic	1	0.00579639	7.34	0.0078
HL*PO Linear	1	0.07574924	95.03	0.0001
HL*PO Quadratic	1	0.00009033	0.11	0.7359
C*HL*PO Linear	1	0.03503694	44.36	0.0001
C*HL*PO Quadratic	1	0.00000039	0.00	0.9822

<sup>a</sup> $Q$  = the software capacitance.

<sup>b</sup> $PR > F$  is the probability that  $F$  value is in the rejection region.

<sup>c</sup> $C$  = the capacitor indicator for either capacitor 1, 2 or 3;

$PO$  = the capacitor position indicator for position 1, 2 or 3;

$HL$  = the humidity level, either high or low.

and position; humidity level and position; and type of capacitor, humidity level, and position. The most beneficial case was the last one because it compares capacitance and all of the variables. The previous two cases are shown in order to infer if any individual combination influences capacitance. Therefore, the last case will be used to accept or reject Hypotheses IX and XI.

When examining the table, it should always be remembered that the enclosed but not ventilated capacitor has been eliminated, due to reasons mentioned in the previous section. It should also be remembered that the statistical level of significance was 95%.

### **Research Hypothesis IX**

It was hypothesized that relative humidity does not affect the capacitance of an unenclosed variable air plate capacitor.

Statistical Research Hypothesis:

Ho:  $Q_{h11} < > Q_{h13}$

Ha:  $Q_{h11} = Q_{h13}$

The sum of squares for the capacitor-humidity level-position-linear variable was 0.035 while, the mean square error was 0.00079. Therefore, F value was equal to  $0.035/0.00079$  or 44.36. The R-square value was 0.9942. To determine if this relationship was significant, F value must be compared with  $F(1,108)$  which was 4.00. Since F value was larger than  $F(1,108)$ , the null hypothesis was rejected.

**Research Hypothesis X**

It was hypothesized that relative humidity does not affect the capacitance of an enclosed but unventilated variable air plate capacitor.

Statistical Research Hypothesis:

$$H_o: Q_{h11} <> Q_{h13}$$

$$H_a: Q_{h11} = Q_{h13}$$

There was no decision for either hypothesis, since the capacitor under study was defective.

**Research Hypothesis XI**

It was hypothesized that relative humidity does not affect the capacitance of an enclosed and vented variable air plate capacitor.

Statistical Research Hypothesis:

$$H_o: Q_{h11} <> Q_{h13}$$

$$H_a: Q_{h11} = Q_{h13}$$

The analysis and explanation are the same as those for Research Hypothesis IX.



## CHAPTER V. SUMMARY AND DISCUSSION OF THE RESULTS

The outline for discussing the outcome of results will be in five parts. The first part will be to restate each research hypothesis and to comment on its experimental interpretation based on its respective statistical result. The second part will be to state what experimental changes occurred. The third part will summarize all concluding remarks. The fourth part will state what recommended changes should be made if future studies were to be taken. The last part will discuss what implications this work has on similar topics in positional positioning.

### Discussion of Research Hypotheses

#### Research Hypothesis I

It was hypothesized that there is no linear relationship between software capacitance and the rotational position of an unenclosed variable air plate capacitor.

#### Discussion of Hypothesis I

Since the null hypothesis was rejected, and there was a high correlation coefficient (0.993), there was a linear relationship between software capacitance and angular displacement.

#### Research Hypothesis II

It was hypothesized that there was no a linear relationship between software measured capacitance and real capacitance of an unenclosed variable air plate capacitor.

### Discussion of Hypothesis II

Since the null hypothesis was rejected and there was a high correlation coefficient (0.984), there was a linear relationship between software capacitance and real capacitance.

### Research Hypothesis III

It was hypothesized that daily environmental changes do not affect the capacitance of an unenclosed variable air plate capacitor.

### Discussion of Hypothesis III

Since the null hypothesis was rejected and there was a high correlation coefficient (0.999), it can be said that daily environmental changes do influence the capacitance of air plate capacitors.

### Research Hypothesis IV

It was hypothesized that the direction of rotation does not affect the rotational position of an unenclosed variable air plate capacitor.

### Discussion of Hypothesis IV

Since the null hypothesis was rejected, and there was a high correlation coefficient (0.999), it can be said that direction of rotation does influence the capacitance of air plate capacitors.

### Research Hypothesis V

It was hypothesized that wet bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

#### Discussion of Hypothesis V

Since the null hypothesis was not rejected and there was a high correlation coefficient (0.999), the wet bulb temperature does not influence capacitance.

#### Research Hypothesis VI

It was hypothesized that dry bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

#### Discussion of Hypothesis VI

Since the null hypothesis was not rejected and there was a high correlation coefficient (0.999), the dry bulb temperature does not influence capacitance.

#### Research Hypothesis VII

It was hypothesized that both wet bulb and dry bulb temperatures do not affect the capacitance of an unenclosed variable air plate capacitor.

#### Discussion of Hypothesis VII

Since the null hypothesis for the case of dry bulb temperature affecting capacitance was accepted, assuming that wet bulb effects are controlled, and had a high correlation coefficient (0.999), it can be stated that dry bulb temperature does not affect capacitance.

Since the null hypothesis for the case of wet bulb temperature affecting capacitance, assuming that dry bulb effects are controlled, was rejected and it had a high correlation coefficient (0.999), it can be stated that wet bulb temperature does affect capacitance. Since

there was an influence by one of the factors, then one should reduce the possibility of error and state that the interaction of both wet and dry bulb temperatures do influence capacitance.

These statements do not strongly conflict with each other. The reason was that the difference between F value and F (1,302) was somewhat small. If many more experimental repetitions were performed, this difference might be reduced. Therefore, through strict logical interpretation, there was an influence between both wet and dry bulb temperatures and capacitance. However, this relationship was not that strong.

#### **Research Hypothesis VIII**

It was hypothesized that an unenclosed variable air plate capacitor can not be used to position a shaft to within 3 degrees of error.

#### **Discussion of Hypothesis VIII**

Since the null hypothesis was rejected and the correlation coefficient was high (0.999), the mean angular error is less than 3.00 degrees. To reduce the amount of possible error for future use, the mean amount of angular error should be doubled. Therefore, an air plate capacitor can be used to position a shaft to within 2 degrees of error.

#### **Research Hypothesis IX**

It was hypothesized that relative humidity does not affect the capacitance of an unenclosed variable air plate capacitor.

Discussion of Hypothesis IX

Since the null hypothesis was rejected and there was a high correlation coefficient (0.994), it can be said that relative humidity does affect the capacitance of an unenclosed variable air plate capacitor.

In the ANOVA, which is an unbalanced one, the order of parameters is important. In the test about whether or not HL has an influence on capacitance values may include the influence of factors C, HL, PO, and the interactions of C\*HL, C\*PO, HL\*PO, and C\*HL\*PO. Therefore, one needs to see the next hypotheses which are used to decide whether or not HL does have an influence to Q.

Ho: Does the three factor interaction, C\*HL\*PO, not have an influence on the capacitive value?

Ha: Does the three factor interaction, C\*HL\*PO, have an influence on the capacitive value?

This can be determined by comparing the F value with a tabular value for F with 1 and 108 degrees of freedom. To do this though, one must remember that C\*HL\*PO has a sum of squares of 0.03503754, a mean square error of 0.00078976 and two degrees of freedom. Thus, the F value was equal to  $(0.03503754/2)/0.00078976$  or 22.18. From the F distribution table,  $F(1,108) = 4.00$ . Since F value  $> F(1,108)$ , we can reject the null hypothesis that the three factor interaction does influence capacitive value.

The type of relationship between the three factors and the

capacitance should be also be examined. This would be most helpful in developing a future predictive equation. The type of relationship can be determined by comparing the F value with a tabular value for F with 1 and 108 degrees of freedom.

The first step was to examine a linear relationship. To do this though, one must remember that C\*HL\*PO LINEAR has a sum of squares of 0.03503694, a mean square error of 0.00078976 and one degree of freedom. From this, the F value was equal to  $0.03503694/0.00078976$  or 44.36. Therefore, there was a significant linear relationship between the three factors and capacitance value.

C\*HL\*PO QUADRATIC has a sum of squares of 0.00000039, a mean square error of 0.00078976 and one degree of freedom. From this, the F value was equal to  $0.00000039/0.00078976$  or 0.000493. Therefore, there was not a significant quadratic relationship between the three factors and capacitance value.

### Research Hypothesis X

It was hypothesized that relative humidity does not affect the capacitance of an enclosed but unventilated variable air plate capacitor.

### Discussion of Hypothesis X

There was no discussion for this hypothesis since the capacitor under study was judged to be defective.



### Research Hypothesis XI

It was hypothesized that relative humidity does not affect the capacitance of an enclosed and vented variable air plate capacitor.

### Discussion of Hypothesis XI

The discussion was the same as that for Research Hypothesis IX.

#### **Experimental Changes**

The results of the study consisted of a number changes from the original proposal. It also consisted of numerous difficulties. The greatest amount of changes occurred in the repeatability experiment because it was complex to build and use. However, the environmental chamber experiment had fewer changes, but it also required more diverse skills to complete it.

### Repeatability experiment

The changes in the experiment involved the mirror alignment system, the sensor interface, the motor control interface, the controlling software, and a few other problems.

There were two changes in the mirror system. The first was that the one foot wide collecting mirror was glued onto a wooden box. As the glue dried or the wood began to swell with the humidity level, enough stress was put on the mirror to break it. The second was that the shaft mirror was glued directly onto the capacitor's rotor, rather than on the coupling. This was done to reduce backlash problems.

The sensor interface had only one problem of trying to produce a filtered, digital signal from the capacitor's analog circuit.

Originally, it was thought that this could be accomplished with integrated circuit timers, counters, and analog-to-digital converters. After many attempts of building these circuits, this was abandoned due to poor facility grounding, poor voltage regulation of various power supplies, and excessive random capacitance from the environment.

Five steps were used to determine this. The first was to use the LM 555 in a one shot mode with a separate power supply than the VIC 20. Despite using various values of resistors and capacitors, an unstable signal was produced. The second step was to use the LM 555 in an astable mode. To verify this, its output was connected to an oscilloscope and a small audio amplifier. The result was an audible sound heard from the speaker, but also the waveform on the scope was a rounded square wave which was superimposed on a larger wave.

The third and fourth steps tried to condition the wave. The third step used a 7404 Hex Buffer integrated circuit to hopefully increase the amplitude and impose a shorter voltage transition time on the LM 555 circuit's output. The result was that the amplitude did increase and the waveform was still "rounded."

The fourth step was to use a Schmitt trigger, enclosed in an HC 7414 integrated circuit, to create the needed voltage transition. In two experiments, its output was both connected and not connected to the 7404 chip. In both cases, the transition was short enough but both waveforms were still enveloped inside of a larger wave. After this, the astable mode was abandoned.

The last step was to try the monostable mode again. This time only the VIC 20's power supply was used. The results were much more stable. Therefore, the monostable mode was chosen as the sensing method.

After this, the circuitry was moved to the Eastern mow of Industrial Education Building II and connected to the capacitor test frame. It was here that a major problem occurred. During various trial runs, it was noticed that when a software capacitance value changed in the program, it always changed in increments of 12. This prompted the question of how much angular rotation and how much capacitance change occurred before the software capacitance changed. The answer to this was found by affixing a protractor on the capacitor and taking measurements (Fig. C.12, Appendix C).

Four attempts were made to obtain higher angular resolution. The first was to compare the incremental changes in the smaller capacitor of the gang with those of the larger capacitor. This failed because the smaller capacitor was defective. After this, another strategy was used to achieve higher angular resolution. It was based on the idea of using a capacitive network similar to that found in a resistive "R-2R" ladder.

The second attempt tried to use an LM 4551 IC analog switch as the switching element in a "C-2C" ladder. This attempt failed because the IC circuit malfunctioned regardless of which 4551 was substituted in the circuit. The third attempt tried to use four SPST relays as switches. The results were that accuracy decreased by twofold.

This could be explained by the circuit's poor grounding or by the inductive and resistive influences of each relay.

The last attempt tried to use an alternative network pattern. The pattern chosen was to use each relay as a capacitance divider. The results were the same as the C-2C network. When these attempts failed, the idea of attaining higher resolution was abandoned due to a lack of time.

The motor control interface was easier to create. To begin with, the four power wires to the motor were spliced with longer wires to make manual control easier. The second item was that a manual power override switch was made to activate the motor from an outlet rather than from its own switch (Fig. C.10, Appendix C). The third item was to use a 7404 inverting buffer to activate a 115 volt, single pole single throw relay.

The last item was that a computer controlled, motor reversing circuit was not constructed. The reasons for this were that there was a shortage of time, and that the motor's wiring diagram was unavailable from the supplier. In view of this, the motor's direction had to be manually controlled.

The controlling software took the most time to create and had four major problems (Fig. E.3, Appendix E). The first was that the FOR . . . NEXT loop which controls the position within a rotation became defective. This was remedied by using a counter. The second problem was that there was difficulty in saving data to a disk. The third problem was that there were two unnecessary stops at the beginning and ending of a rotation. The last problem occurred during the trial runs.

During this time, it was discovered that keying in data to the VIC 20, in order to get a hardcopy, required twice as much time as manual data recording. The manual option was taken since the experiment had to be completed within a three-week period.

The problems encountered with the repeatability experiments led to additional experiments. The first of the two problems was the assumption that the motor's rotation would create a perfect angular sector that was simply diverted by the mirror system. However, after re-analysis of the problem it was determined that the position of each mirror had to be measured. This was done with the fixture shown in Fig. C.11 of Appendix C. It functions on the idea that the laser beam shines parallel to the slots on the fixture. Since the members of the fixture are perpendicular or parallel to each other, a good reference frame was created. The measured results are in Table 8.

A Pascal program was written to help process the data (Fig. E.4, Appendix E). Despite many attempts to condition the data, the processed angular data did not represent the results of the real experiment. The reason for this was due to human error in measurement. Therefore, the angular positions were calculated from software capacitance.

As a result of these new calculations, it was found that the direction of rotation had an influence on the angular position of the shaft with respect to a target value. In addition, it was found that the distance between the collecting mirror and fine adjustment mirror were greatly reduced.

Environmental chamber experiment

The changes in this experiment dealt with data gathering, the type of hygroscopic salts used, and the computer interface. For a given position, two humidity levels were recorded. For each humidity level, 84 samples were gathered. Each sample consisted of the average of 350 observations. Each sample was taken every two minutes. There were no programming problems (Fig. E.5, Appendix E).

Table 8. Geometric Data for the Repeatability Experiment<sup>a</sup>

Shaft Co-ordinates: X=-3367, Y= -19

Mirror Co-ordinates

	Beginning Point		Ending Point	
	X	Y	X	Y
Mirror 1	-3180	79	-3202	132
Mirror 2	-3201	150	-3227	201
Mirror 3	-3298	262	-3341	311
Mirror 4	-3418	92	-3476	127
Collect. Mirror	-7430	785	-7391	1912
Wall	0	0	7	81

<sup>a</sup>All measurements are in millimeters.

The two humidity levels were approximately 70% and 97%+. The lower humidity salt was ammonium chloride ( $\text{NH}_4\text{Cl}$ ) and the higher humidity salt was cuprous sulfate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ). Both salts performed well except for the cuprous sulfate. After the first drying cycle, it turned from a



brilliant deep blue to a light blue (Figs. D.11 and D.12, Appendix D). After consulting with a chemist, it was suggested that the heat from the gas drying oven may have dried the salt out too quickly. This observation was hard to verify, since the humidity level of cuprous sulfate was very close to that of water in an open container.

The computer interface had one unanticipated problem (see Figs. D.13 and D.15, Appendix D). As each LM 555 timer was connected to the computer, the overall capacitance increased. This was notable, since each LM 555 was supposed to be electrically isolated from each other.

### **Conclusions of the Study**

1. There was a linear relationship between capacitance and the rotational position of an unenclosed variable air plate capacitor.
2. In the repeatability experiment there was a linear relationship between software capacitance and real capacitance.
3. In the repeatability experiment, daily environmental changes affect the capacitance of an unenclosed variable air plate capacitor.
4. In the repeatability experiment, the direction of rotation does have a significant effect on the rotational position of a variable air plate capacitor.
5. In the repeatability experiment, wet bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.

6. In the repeatability experiment, dry bulb temperature does not affect the capacitance of an unenclosed variable air plate capacitor.
7. In the repeatability experiment, the combination of both wet and dry bulb temperatures slightly affect the capacitance of a variable air plate capacitor.
8. An unenclosed variable air plate capacitor can be used to position a shaft to within 2 degrees of error.
9. In the environmental chamber experiment, relative humidity did not significantly affect the capacitance of either the unenclosed or vented capacitors.
10. No relationship between humidity and capacitance can be drawn from the enclosed but unvented capacitor experiment.

#### **Recommendations of the Study**

1. In order to measure shaft rotations, use an encoder that can be interfaced to a computer and is accurate to 0.01 degrees.
2. Extend the study to a year in length in order to sample as many environmental conditions as possible.
3. Perform a longer pilot study whose results are statistically significant.
4. Design the long term experiment along statistical methods before it is executed.
5. Use more differing humidity and temperature levels.
6. For future study, include barometric pressure observations.
7. Use a multi-element gang capacitor, with a hardware

- monitoring system, to increase accuracy and response time.
8. Increase the capacitance of the sensor by using large plates with narrower gaps.
  9. Increase the capacitance by using an insulator with a large dielectric constant, such as silicone, teflon, grease, etc.

### **Implications of the Study**

This study examined the possibilities of how a variable capacitor could be used as a sensor in a positioning system. It's research effort tried to determine if it was possible for such a device to function reliably outside of a laboratory setting. Since the capacitor could help position a shaft to within 2 degrees of error, based on using air as a dielectric, an improved component could have a significant impact on machine tool control.

The impact is determined by two factors. The first is that software was used to sense, decide, and implement a movement. The process is inherently slow because the information must be converted from an analog to digital signal, processed from a set of human readable commands, averaged, compared, resolved, and converted to a control signal. This is much more complex since a hardware process responds directly to electrical stimuli, rather than a logic conversion process. A hardware system's advantage could be the subject of a future study.

The second part is that air was used as a dielectric. This is important, since air is one of the worst insulators known. For example, if the capacitor had been immersed in oil, which has between 2 to 5 times as much the dielectric strength of air, the accuracy could have

been increased to about  $1/2$  of one degree. This accuracy could have made such an encoder attractive as a directly linked sensor on one of the shafts of an X-Y table.

A capacitive encoder could be a competitive alternative to optical encoders or resolvers where the resolution tolerance is between 0.01 and 1.0 degrees. There are two major reasons for this. The first is that there are many machine tool and pick-and-place applications which fall into this range. The second is that the added expense of a highly precise encoder is unjustified for the inaccurate uses found in this range. Therefore, from an economic viewpoint, a capacitive encoder for this range could be attractive.

There are three other reasons favoring a capacitive encoder. The first is that it is relatively immune from the electrical problems of power line surges and stray magnetic fields. The second reason is that it is lighter than a resolver, which makes it a likely sensor choice for the end of arm tooling on robots. The last reason is that its continuous output reduces the misalignment or light intensity errors involved with optical encoders.

The final result of this study is far from being attained. The basic questions of whether it is possible to use a software driven, capacitive encoder have been answered. Future steps would be directed toward gathering statistically significant data from daily experience. Eventually, these efforts will produce the means by which more economic products can be made.

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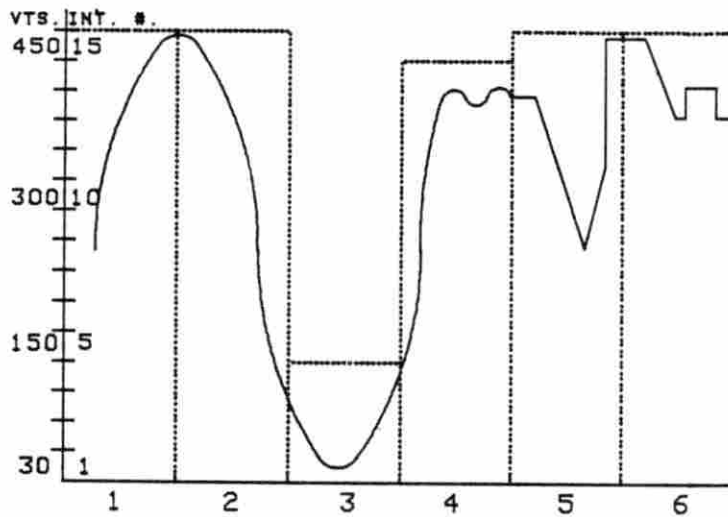
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## APPENDIX A. ANALOG TO DIGITAL CONVERSION

Fig. A.1. Digitized analog signal with code conversion



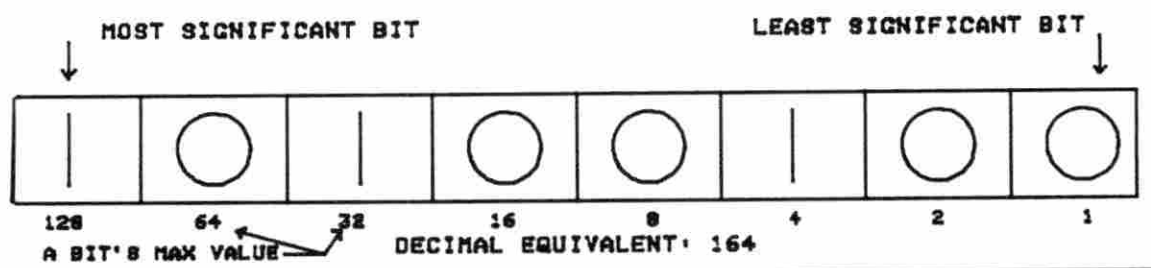
TIME INTERVAL  
(1/100 SEC.)

COMPARISON BETWEEN ANALOG AND DIGITAL MEASUREMENT

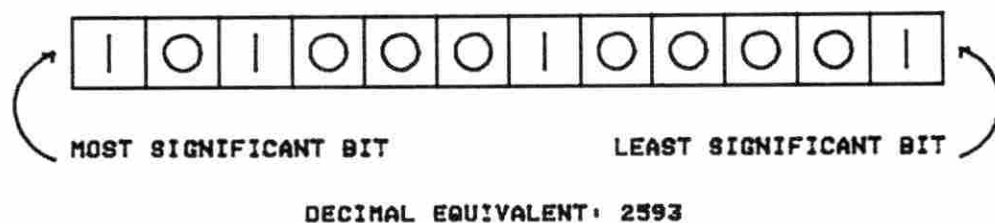
TIME INT. #	1	2	3	4	5	6
MAX. ANALOG VALUE (VOLTS)	44.5	44.6	10.8	39.4	44.3	44.3
DIGITIZED VALUE (VOLTS)	45	45	12	42	45	45
DECIMAL INTERVAL VALUE	15	15	4	14	15	15
BINARY VALUE OF DEC. INT.	1111	1111	0100	1110	1111	1111

Fig. A.2. Examples of eight bit and twelve bit words

## EIGHT BIT WORD (OR BYTE)



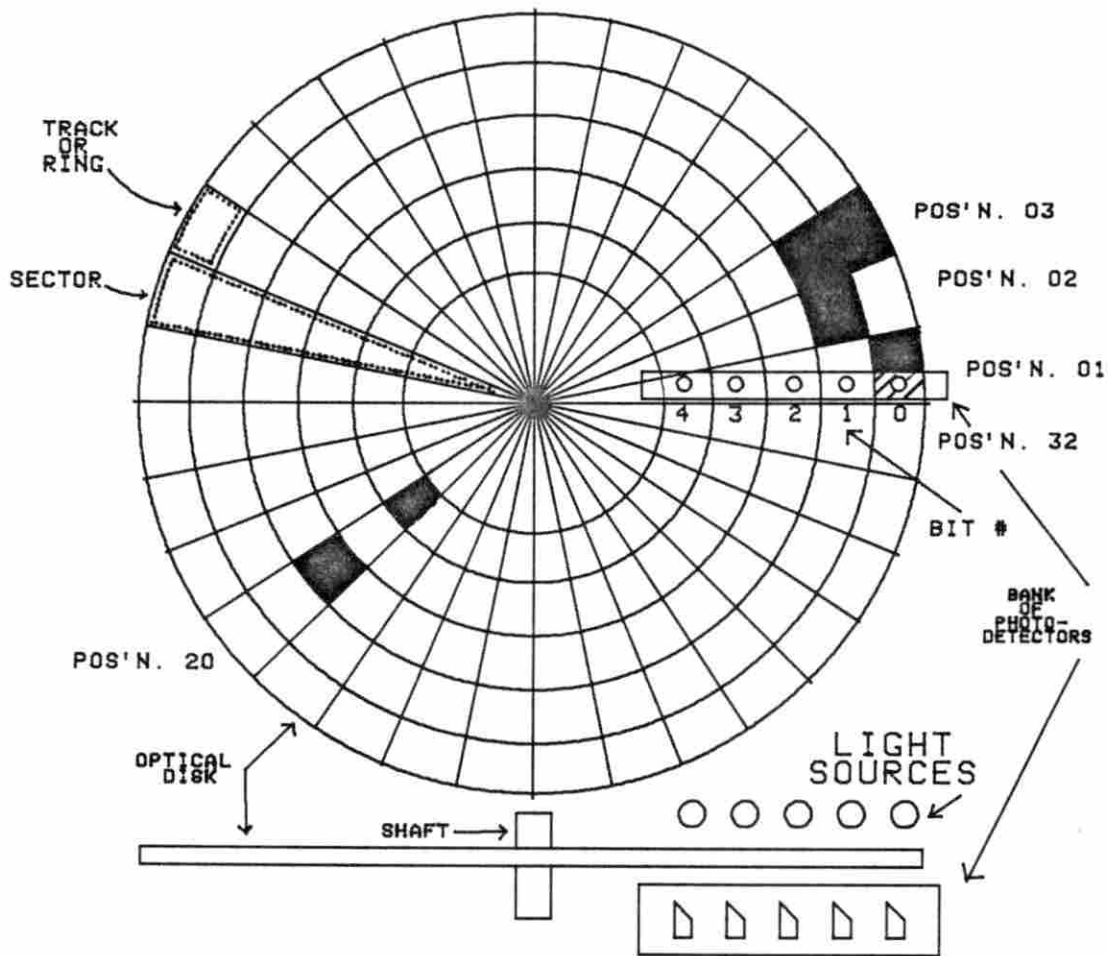
## TWELVE BIT WORD (OR BYTE)



APPENDIX B. OPTICAL ENCODER DISK CONFIGURATIONS



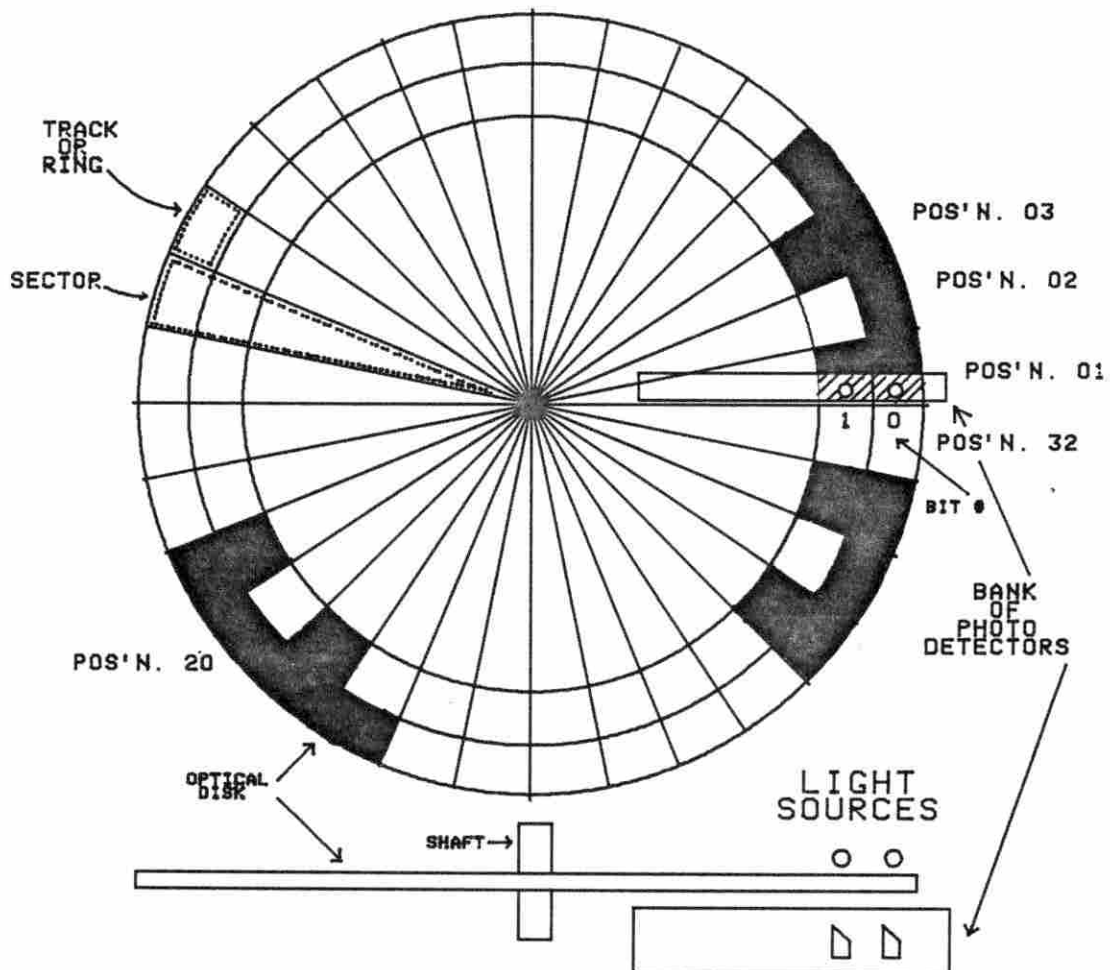
Fig. B.1. An optical, absolute, rotary encoder



NOTE: BINARY PATTERNS ARE NOT SHOWN IN ALL POSITIONS.

BIT #	PHOTO DET.	STATUS	4	3	2	1	0
LOGIC LEVEL	OFF	LO	OFF	LO	OFF	LO	ON
BINARY EQUIVALENT	0	0	0	0	0	0	1
DECIMAL EQUIVALENT: 1							

Fig. B.2. An optical, incremental, rotary encoder



NOTE: ELECTRONIC COUNTERS ARE NOT SHOWN.

BIT #	1	0
DETECTOR STATUS	ON	ON
LOGIC LEVEL	HI	HI
BINARY EQUIVALENT	1	1
BINARY COUNT: 0000 0001		
DECIMAL EQUIVALENT: 1		

APPENDIX C. FIGURES AND TABLES RELATING TO  
REPEATABILITY EXPERIMENT

Fig. C.1. Original radio set. Note capacitor in the lower right corner

Fig. C.2 Capacitor test frame (front view). Note the two foot ruler, marked off in inches, standing in it

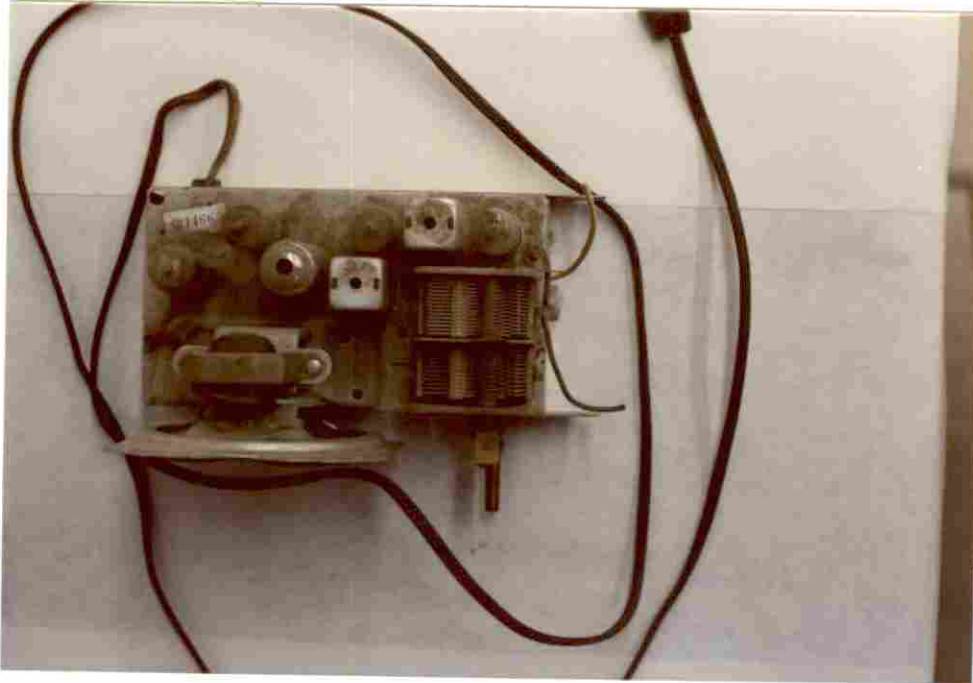




Fig. C.3. Capacitor test frame (back view)

Fig. C.4. Motor module

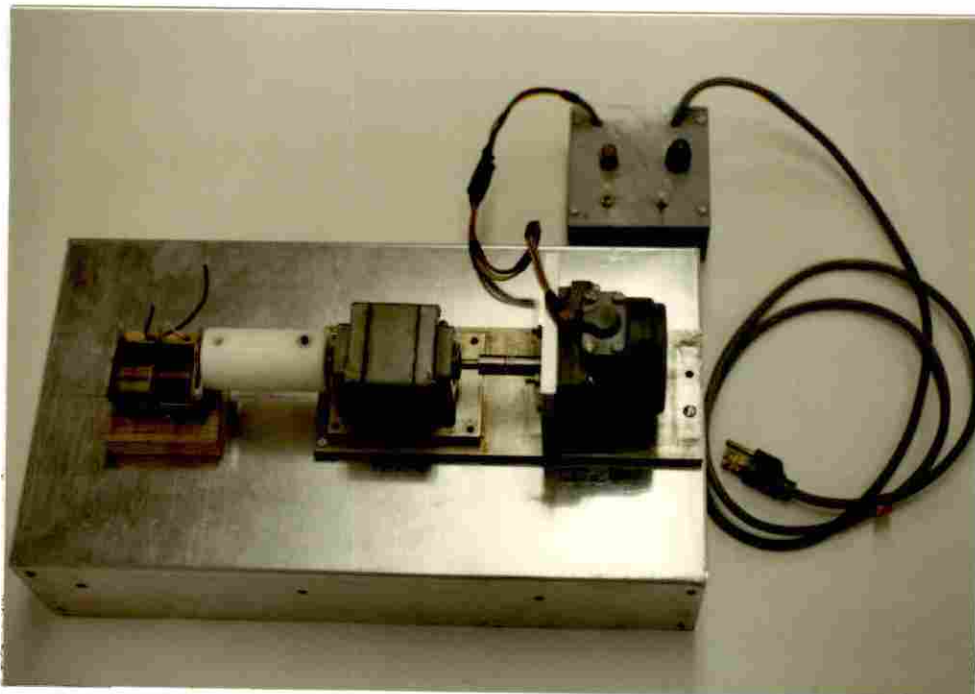


Fig. C.5. Repeatability experiment interface

Fig. C.6. Mirror alignment system

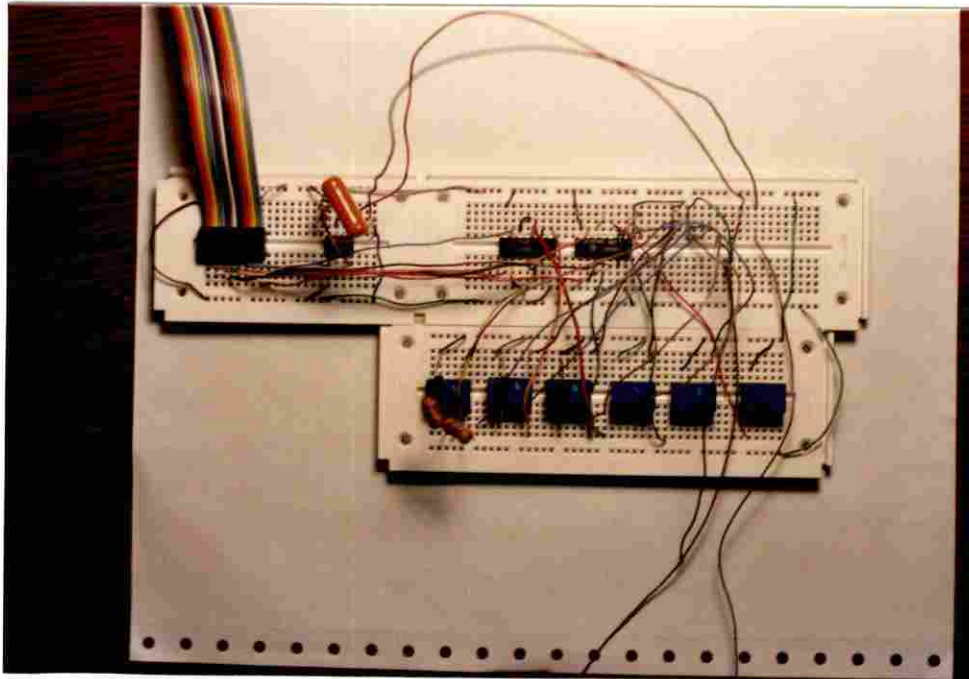


Fig. C.7. Fine adjustment mirror (unassembled)

Fig. C.8. Collector mirror (front view)

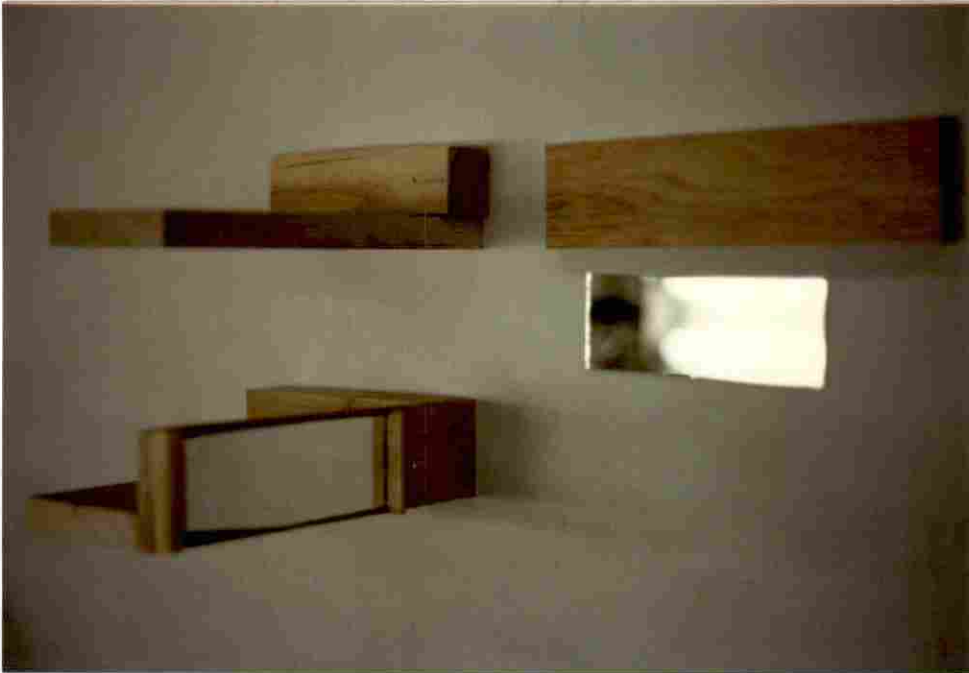


Fig. C.9 Collector mirror (back view)

Fig. C.10. Manual override switch



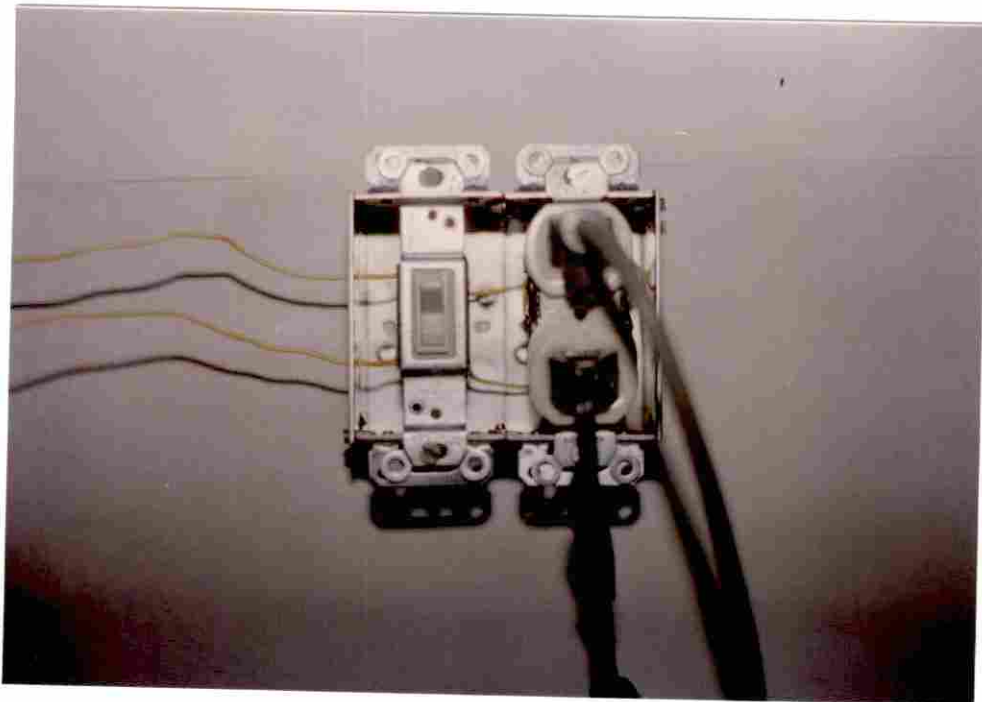


Fig. C.11. Geometric measurement fixture (top view)

Fig. C.12. Angular measurement fixture (top view)

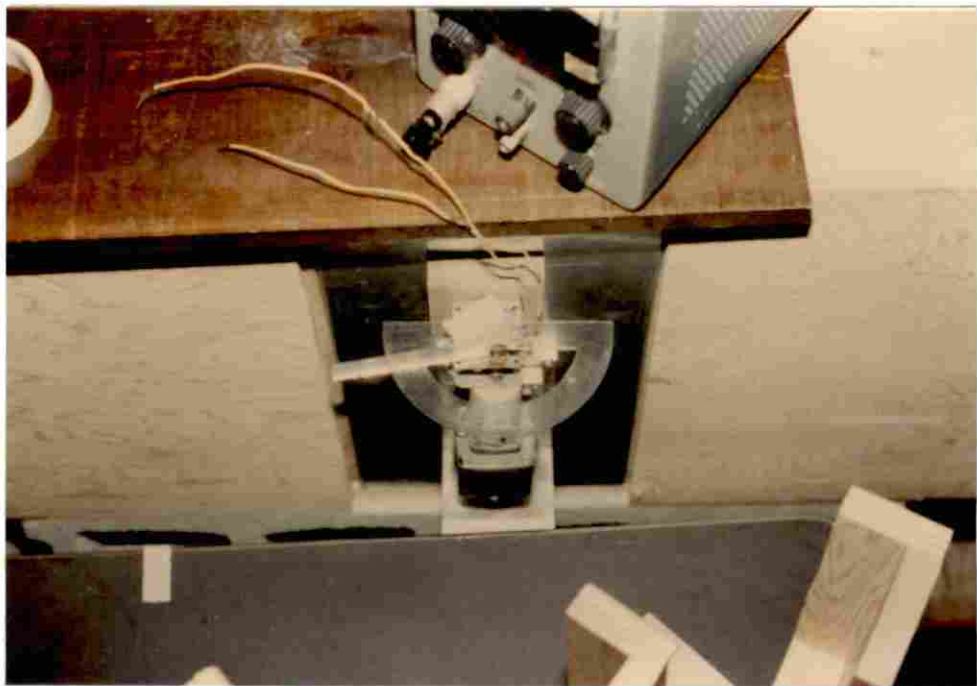
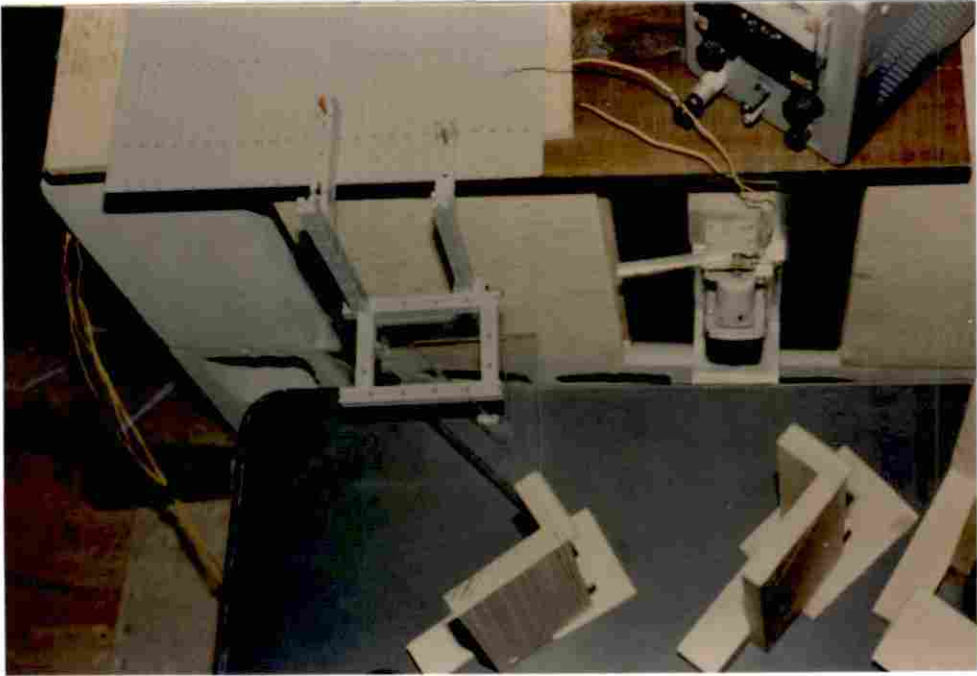
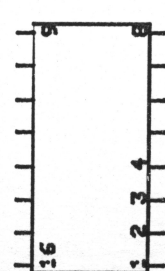
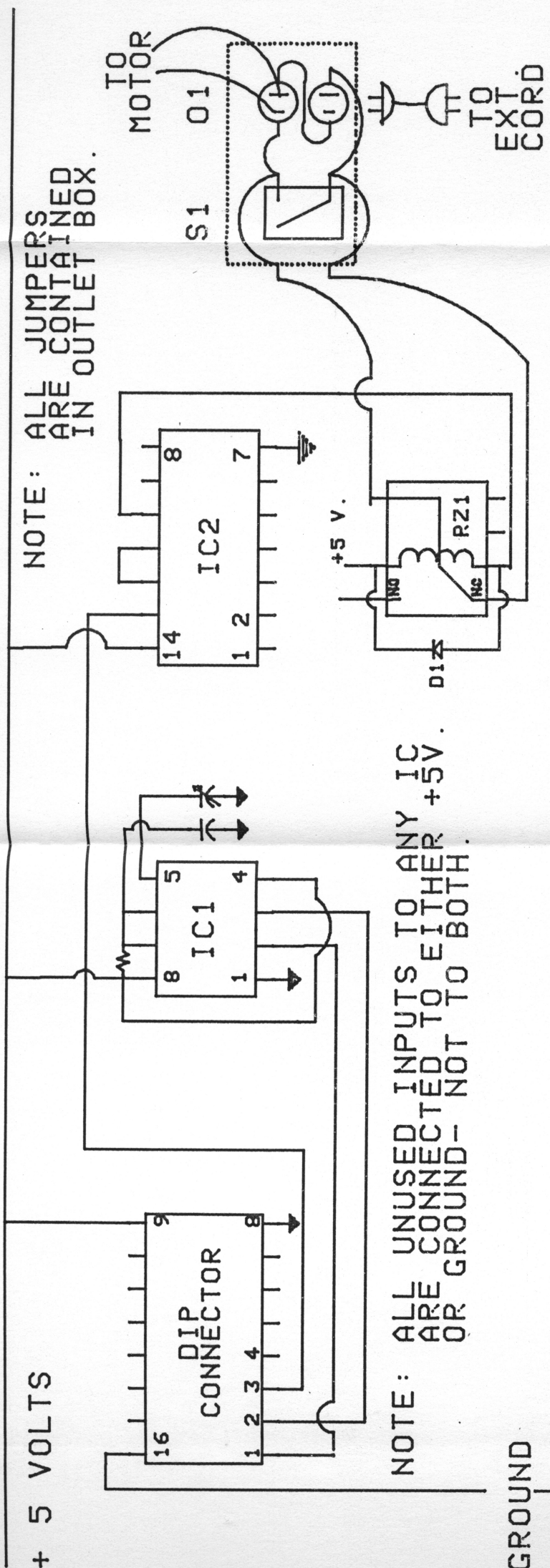
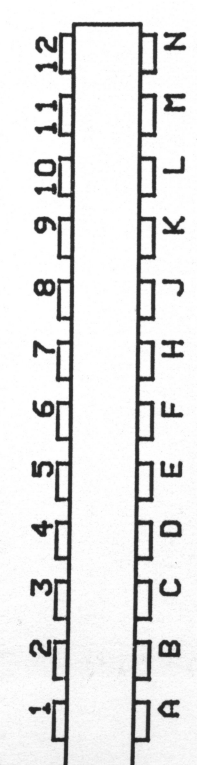


Fig. C.13 Schematic for repeatability experiment



### PARALLEL USER PORT



< TOP >

### PINOUT SUMMARY

TYPE	PORT	DIP	REMARKS
BIT #	0	1	MONITORS ON IC1
"	1	2	MONITORS ON IC1
"	2	3	TURNERS ON IC2
"	3	4	TURNERS ON IC2
"	4	5	UNUSED
"	5	6	"
"	6	7	"
"	7	8	"
"	8	9	"
"	9	10	"
"	10	11	"
"	11	12	"
"	12	13	"
"	13	14	"
"	14	15	"
"	15	16	"
"	16	17	"
"	17	18	"
"	18	19	"
"	19	20	"
"	20	21	"
"	21	22	"
"	22	23	"
"	23	24	"
"	24	25	"
"	25	26	"
"	26	27	"
"	27	28	"
"	28	29	"
"	29	30	"
"	30	31	"
"	31	32	"
"	32	33	"
"	33	34	"
"	34	35	"
"	35	36	"
"	36	37	"
"	37	38	"
"	38	39	"
"	39	40	"
"	40	41	"
"	41	42	"
"	42	43	"
"	43	44	"
"	44	45	"
"	45	46	"
"	46	47	"
"	47	48	"
"	48	49	"
"	49	50	"
"	50	51	"
"	51	52	"
"	52	53	"
"	53	54	"
"	54	55	"
"	55	56	"
"	56	57	"
"	57	58	"
"	58	59	"
"	59	60	"
"	60	61	"
"	61	62	"
"	62	63	"
"	63	64	"
"	64	65	"
"	65	66	"
"	66	67	"
"	67	68	"
"	68	69	"
"	69	70	"
"	70	71	"
"	71	72	"
"	72	73	"
"	73	74	"
"	74	75	"
"	75	76	"
"	76	77	"
"	77	78	"
"	78	79	"
"	79	80	"
"	80	81	"
"	81	82	"
"	82	83	"
"	83	84	"
"	84	85	"
"	85	86	"
"	86	87	"
"	87	88	"
"	88	89	"
"	89	90	"
"	90	91	"
"	91	92	"
"	92	93	"
"	93	94	"
"	94	95	"
"	95	96	"
"	96	97	"
"	97	98	"
"	98	99	"
"	99	100	"

NOTE: ALL OTHER PINS ON PORT & DIP ARE UNUSED

THE PORT PINOUT WAS FOUND IN FINKEL et al. (1982). THE DIP CONNECTOR PINOUT WAS FOUND IN SMIDT (1984).

Fig. C.14. Electronic hardware component list

**Component List for Repeatability Experiment**

C1- 0.1 microfarad electrolytic capacitor

C2- 100-300 (approx.) picofarad variable air plate capacitor

D1- 1N4001 200 volt, 1 ampere diode

Dip connector- 16 pin, dual-in-line-package connector with  
rainbow ribbon cable

Edge connector- 12/24 pin

IC1- LM 555 timer

IC2- 7404 Hex inverter

O1- Duplex outlet rated at 120 volts @ 15 amperes

S1- Single pole silent switch; rated at 120 volts @ 15 amperes

R1- 1,000,000 ohm, 5% precision, graphite, axial resistor

RZ1- 5 Volt, single pole, single throw, printed circuit board  
mounted relay; rated at 100 volts @ 1 ampere

Assorted lengths of connecting wire

APPENDIX D. FIGURES AND TABLES RELATING TO  
ENVIRONMENTAL EXPERIMENT



Fig. D.1. Scatterplot of capacitor 1, low humidity

Fig. D.2. Scatterplot of capacitor 1, high humidity

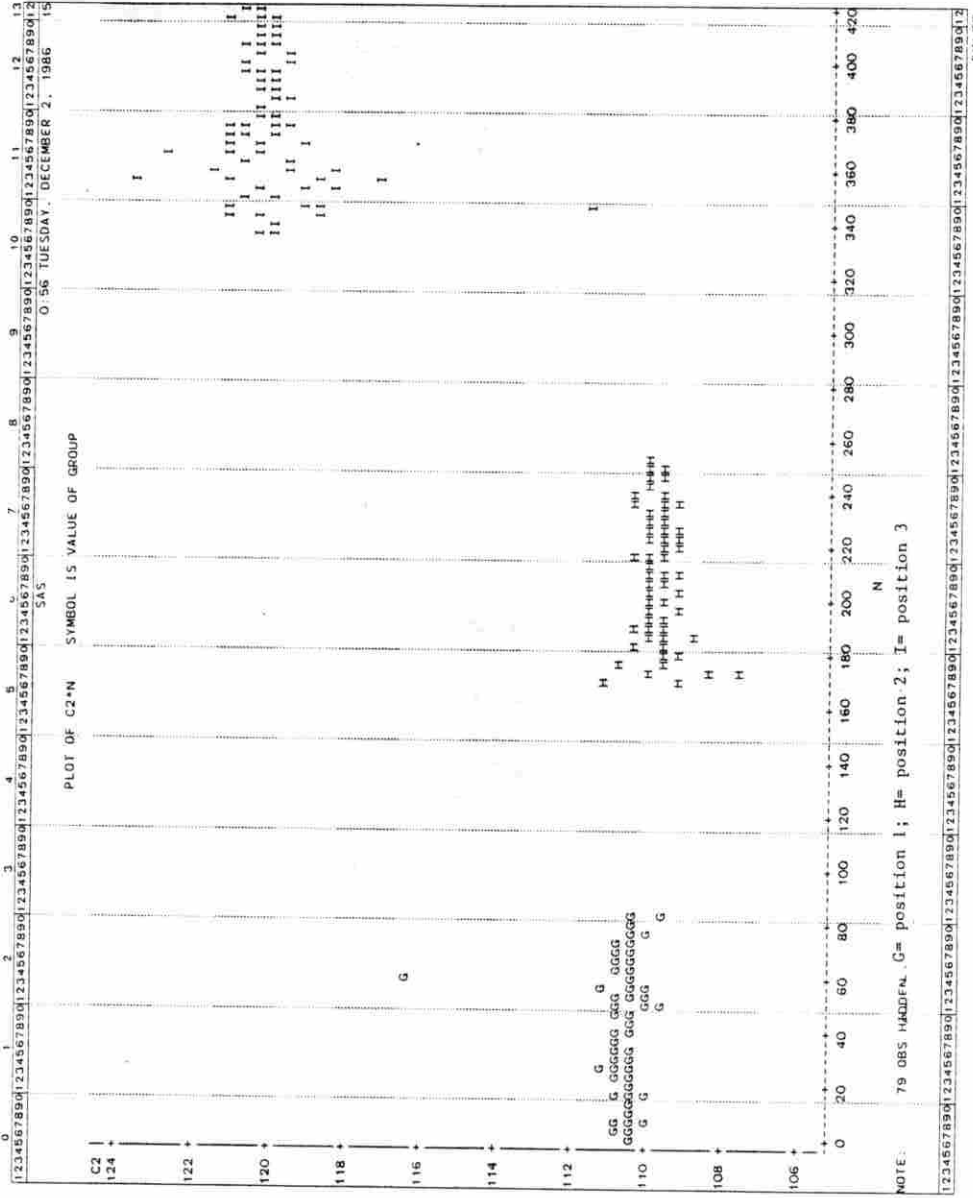


Fig. D.3. Scatterplot of capacitor 2, low humidity

Fig. D.4. Scatterplot of capacitor 2, high humidity

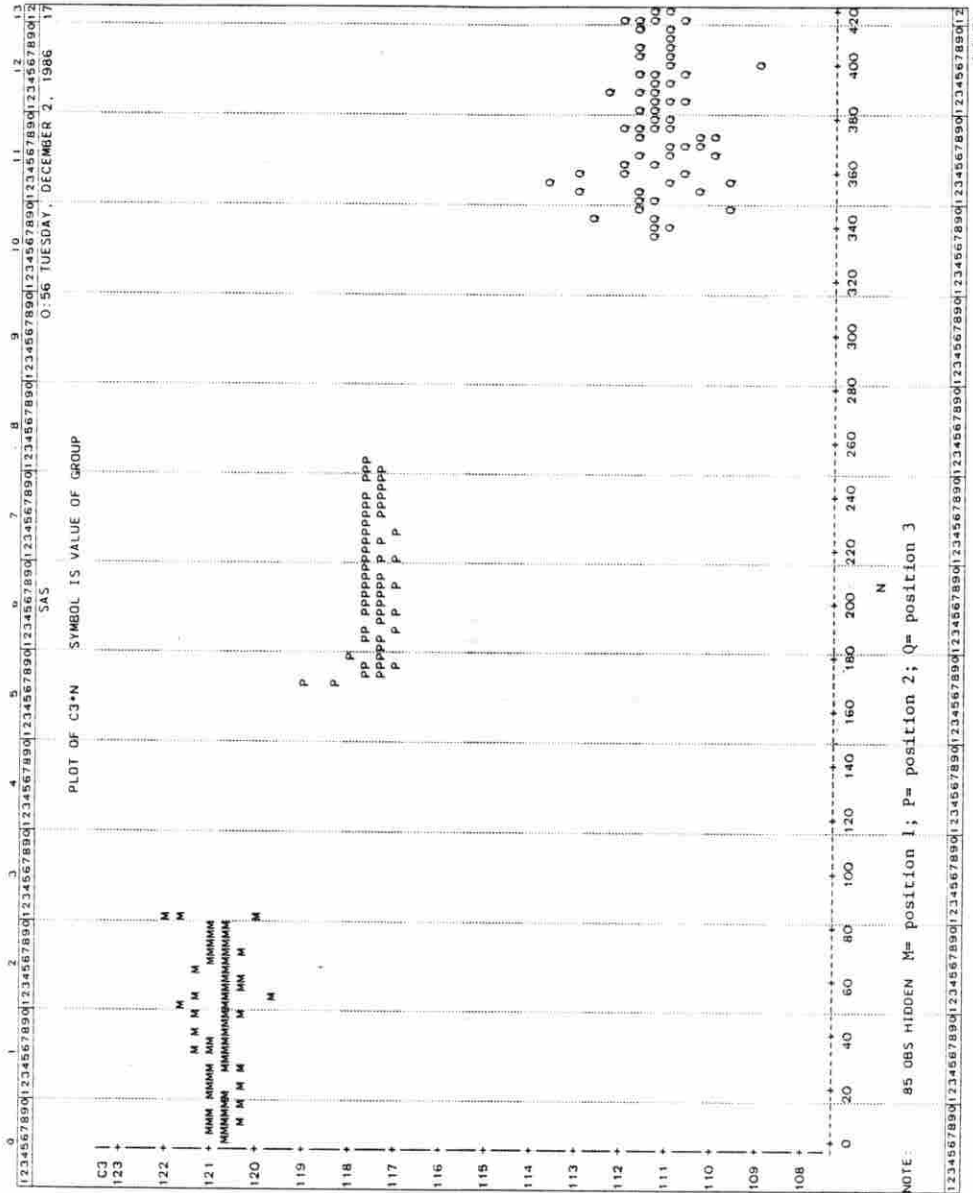


Fig. D.5. Scatterplot of capacitor 3, low humidity

Fig. D.6. Scatterplot of capacitor 3, high humidity

Fig. D.7. Old chart recorder (with door closed)

Fig. D.8. Old chart recorder (with door open)





Fig. D.9 Chart recorder box with mechanisms removed

Fig. D.10. Environmental chamber with components mounted in it

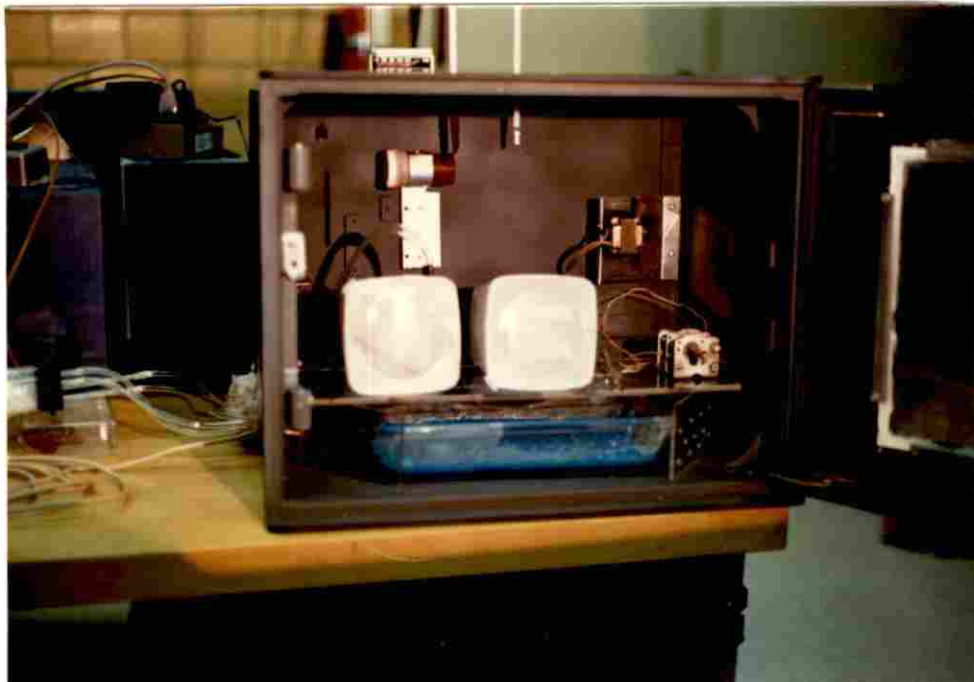
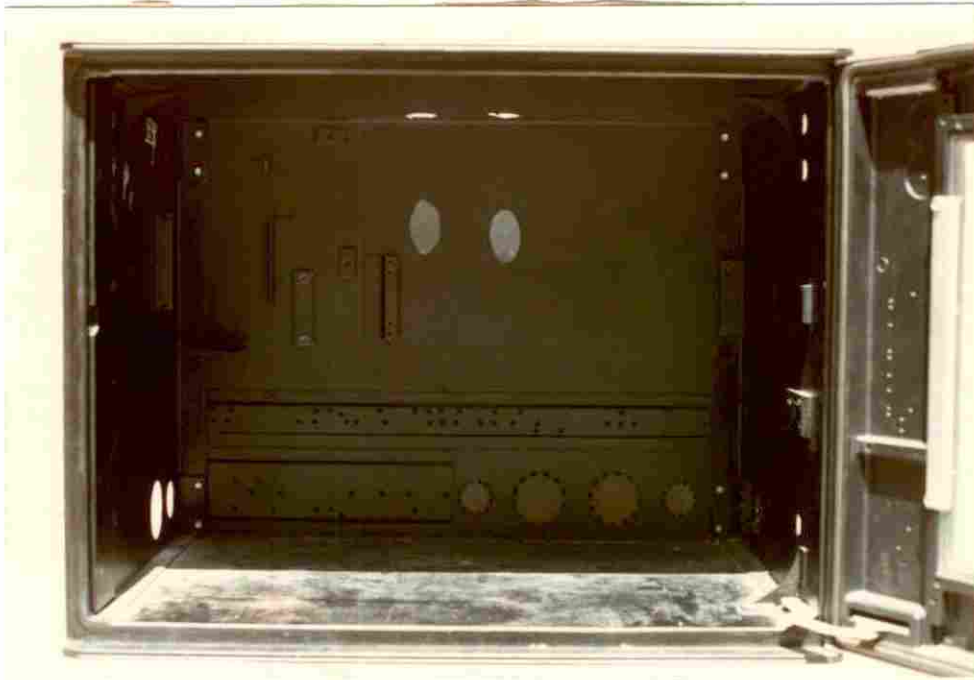


Fig. D.11. Environmental experiment humidity salts. Note ammonium chloride (left) and copper sulfate (right)

Fig. D.12. Thermal change of copper sulfate after excessive drying



Fig. D.13. Capacitive monitor interface with VIC 20

Fig. D.14. Front view of environmental experiment apparatus

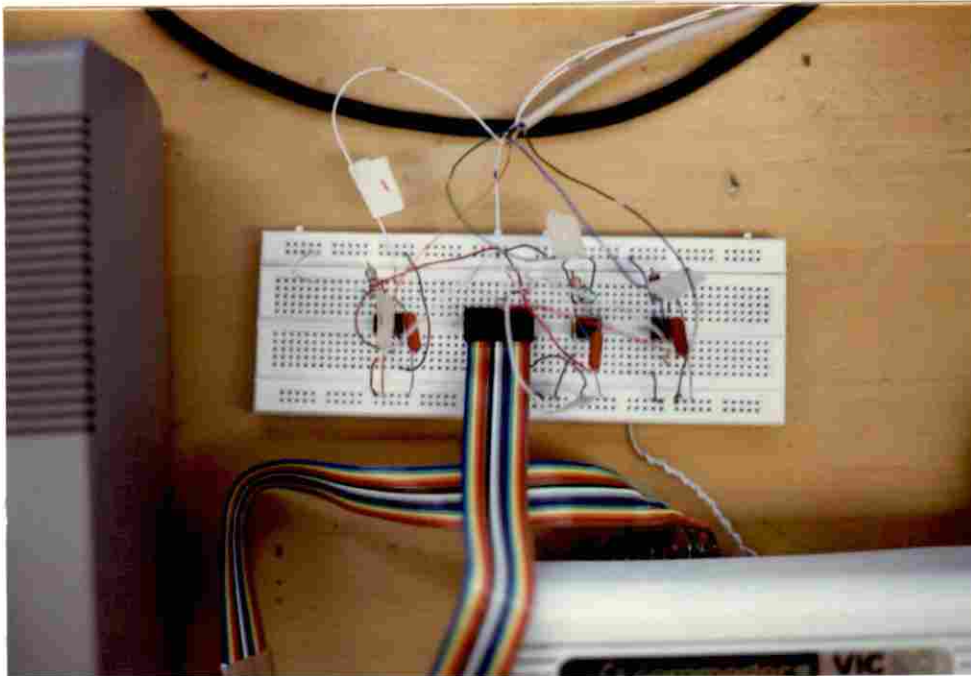
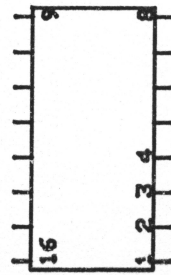
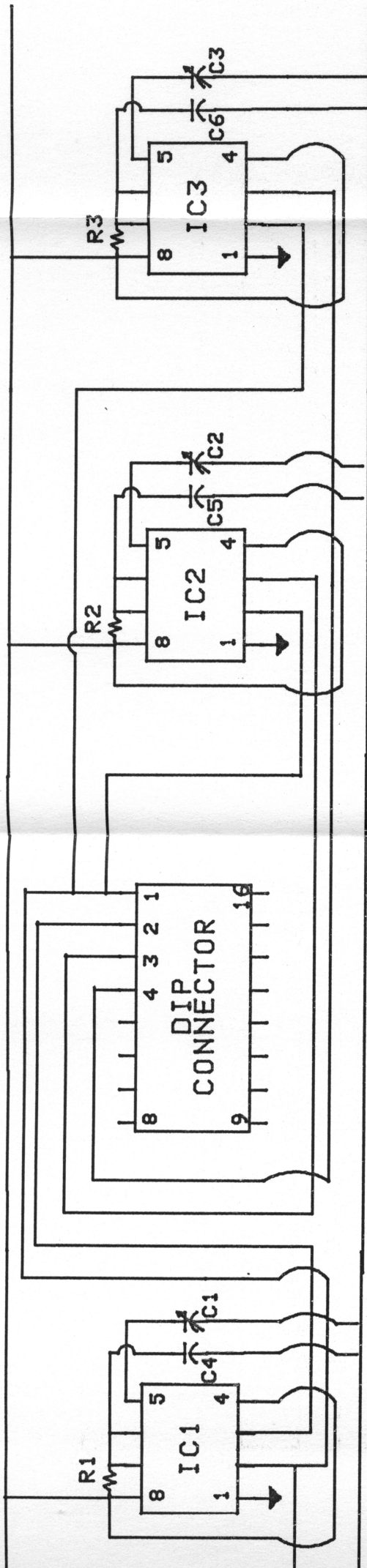


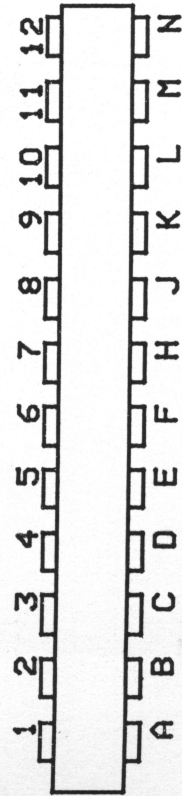
Fig. D.15. Schematic for environmental experiment



DIP CONNECTION END OF RIBBON JUMPER CABLE

# PARALLEL USER PORT

< TOP >



< LOOKING AT THE MALE CONNECTOR FROM OUTSIDE THE COMPUTER >

## PINOUT SUMMARY

TYPE	PORT	DIP	REMARKS
BIT #0	1	2	1
"	2	3	2
"	3	4	3
"	4	5	4
"	5	6	5
"	6	7	6
CB 1	8	8	7
CB 2	9	9	8
+5V	10	10	9
GROUND	11	11	10
	12	12	11
	13	13	12
	14	14	13
	15	15	14
	16	16	15

NOTE: ALL OTHER PINS ON PORT & DIP ARE UNUSED

THE PORT PINOUT WAS FOUND IN THE FINKEL et al. (1982). THE DIP CONNECTOR PINOUT WAS FOUND IN SMIDT (1984)



Fig. D.16. Electronic hardware component list

**Component List for Environmental Experiment**

C1, C3- 100-300 (approx.) picofarad, clockwise rotating,  
variable air plate capacitor

C2- 300-600 (approx.) picofarad, counterclockwise rotating,  
variable air plate capacitor

C4, C5, C6- 0.1 microfarad electrolytic capacitor

Dip connector- 16 pin, dual-in-line-package connector with  
rainbow ribbon cable

Edge connector- 12/24 pin

IC1, IC2, IC3- LM 555 timer

R1, R2, R3- 1,000,000 ohm, 5% precision, graphite, axial  
resistor

Assorted lengths of connecting wire

APPENDIX E. HARDCOPIES OF COMPUTER SOFTWARE

Fig. E.1. MLTIMER program

**MLTIMER Program**

Location		Machine Code			
Decimal	Hex	Mnemonics	Hex	Decimal	Comments
828	033C	-	-	-	count value, low byte
829	033D	-	-	-	count value, high byte
830	033E	LDX #00	A2 00	162,0	prepare to count
832	0340	LDY #00	A0 00	160,0	
834	0342	LDA A2	A5 A2	165,162	wait for clock to change
836	0344	CMP A2	C5 A2	197,162	
838	0364	BEQ 0344	F0FC	240,252	
840	0348	LDA 9110	AD 10 91	173,16,145	low pulse in pin 1
843	034B	AND #FE	29 FE	41,254	
845	034D	STA 9110	8D 10 91	141,16,145	
848	0350	ORA #01	09 01	9,1	
850	0352	STA 9110	8D 10 91	141,16,145	
853	0355	LDA #02	A9 02	169,2	start of check loop
855	0357	BIT 9110	2C 10 91	44,16,145	check bit 2
858	035A	BEQ 0362	F0 06	240,6	
860	035C	INX	E8	232	count
861	035D	BNE 0357	DO F8	208,248	
863	035F	INY	C8	200	
864	0360	BNE 0357	DO F5	208,245	
866	0362	STX 033C	8E 3C 03	142,60,3	save count and exit
869	0365	STY 033D	8C 3D 03	140,61,3	
872	0368	RTS	60	96	

Note: This program may be invoked by the statement "SYS 830". It will send a low pulse on pin 1 then wait for pin 2 to go low. It may be modified as follows:

Location	Present Value	Description
844	254	Mask - All bits 1 except bit to go low
848	1	Bit in position of output to go high
854	2	Bit in position of input

### **Program Explanation**

The MLTIMER program is a machine language program which utilizes two of the eight output ports of the VIC 20 parallel user port. It is loaded into the cassette memory area of the VIC 20. The program can be outlined as follows:

1. Simultaneously poke a logic high signal out of port 1 and start an internal timer in the VIC 20. The value to be poked out is 1.
2. Monitor port 2 for an input signal by peeking the value of 2 to the output port.
3. When a logic high has been sensed, the program will simultaneously stop the timer and store the value in memory address 869.

The main program then peeks memory value 869 to determine how much time has elapsed since MLTIMER was activated.

### **Explanation of Repeatability Experiment Program**

The repeatability experiment program uses MLTIMER to determine the status of an LM 555 timer in a one shot mode. The description which describes this is:

1. Start MLTIMER by sending a logic high signal out through port 1 of the VIC 20.
2. Wait until the variable capacitor, C2, charges up to 2/3 of Vcc. When this occurs, stop MLTIMER.

3. Peek into memory location 869 and assign its value to CP.
4. Repeat steps 1-3 four more times to achieve the running sum  
which is to be averaged.

Continue the BASIC program as described.

### **Explanation of Environmental Experiment Program**

The environmental experiment program uses MLTIMER to determine the status of three LM 555 timers in a one shot mode. The description which describes this is:

1. Start MLTIMER by sending a logic high signal out through  
port 1 of the VIC 20.
2. Wait until the variable capacitor, C2, charges up to  $2/3$  of  
Vcc. When this occurs, stop MLTIMER.
3. Peek into memory location 869 and assign its value to CP.
4. Repeat steps 1-3 four more times to achieve the running sum  
which is to be averaged.
5. Poke port 3 to stimulate the LM 555 timer for capacitor 2.  
This is done by poking out the value of 4.
6. Repeat steps 2-4 for capacitor 2.
7. Repeat steps 5 and 6 for capacitor 3. This is done by poking  
out the value of eight through port 4.

Fig. E.2. TLAB8 program



```
10 POKE37138,1
12 SYS830:PRINT PEEK(829)*3077+12*PEEK(828)+12;"MICROSECONDS"
14 FORI=1TO100:NEXT
15 GOTO12
```

Fig. E.3. Repeatability experiment program

```

100 REM
110 REM
120 REM
130 REM
140 REM
150 REM
160 REM
170 REM
180 REM
190 REM
200 REM
210 REM
220 REM ***** VARIABLE DICTIONARY *****
230 REM AF$= A CHRACTR. VARIABLE USED TO INDICATE A FILE DIRECTORY ON THE DISK
240 REM AV= SAMPLE AVERAGE OF 'OM' CAPACITANCE OBSERVATIONS
250 REM DIRECTORY.
260 REM BEENHERE$= A STATUS VARIABLE THAT KEEPS TRACK OF WHETHER A MENU'S BEEN
270 REM USED
280 REM BF$= A PREVIOUS DIRECTORY FILE NAME BEFORE A NEW FILE IS ADDED
290 REM CH= AN INDEX VARIABLE THAT CHANGES THE INPUT VARIABLES
300 REM CP= CAPACITANCE VALUE AS MEASURED IN PEAK TO PEAK MICROSECONDS
310 REM D(GP,PO,C)= A REAL DATA ARRAY THAT STORES SPOT GEOMETRY & CAPACITANCE
320 REM GP= THE SAMPLING GROUP NUMBER (SEE BELOW)
330 REM PO= THE POSITION NUMBER (SEE BELOW)
340 REM C= THE SPOT OR CAPACITANCE VALUE
350 REM D(GP,PO,1)= RIGHT SIDE OF THE SPOT
360 REM D(GP,PO,2)= LEFT SIDE OF SPOT
370 REM D(GP,PO,3)= BOTTOM OF SPOT
380 REM D(GP,PO,4)= TOP OF SPOT
390 REM D(GP,PO,5)= THE SAMPLE CAPACITANCE
400 REM DIS= THE DIRECTORY LIST FILE
410 REM DB(GP)= A REAL ARRAY USED TO STORE DRY BULB TEMPERATURE
420 REM DD= DATA DIRECTION REGISTER FOR THE VIC 20 OUTPUT PORT
430 REM DR$= THE STRING VARIABLE WHICH INFORMS THE USER IN WHICH DIRECTION THE
440 REM MOTOR
450 REM IS TURNING.
460 REM GMAX= THE MAXIMUM NUMBER OF SAMPLING GROUPS IN THIS DATA FILE.
470 REM GP= A COUNTER WHICH INDICATES THE PRESENT SAMPLING GROUP NUMBER
480 REM HC= AN INDEX VARIABLE THAT CHANGES FILE OPTIONS
490 REM IDMAX= CONTAINS 4 SPOT BOUNDARY READINGS AND THE CAPACITANCE
500 REM J= A COUNTER FOR THE MOTOR OFF WAITING LOOP.
510 REM JJ= A COUNTER USED TO FILL THE CAPACITVE TARGET ARRAY
520 REM K= A COUNTER FOR THE MOTOR ON RUNNING LOOP.
530 REM L= A COUNTER USED TO INITIALIZE THE PREVIOUS DIRECTORY ARRAY
540 REM LO= A COUNTER USED TO SEND OUT THE NEW DIRECTORY FILE
550 REM MAX= A REAL VARIABLE THAT HOLDS THE MAXIMUM CAPACITANCE OBSERVATION
560 REM MIN= A REAL VARIABLE THAT HOLDS THE MINIMUM CAPACITANCE OBSERVATION
570 REM MCS= AN INDEX VARIABLE THAT CHOOSES THE MOTOR CONTROL MODE
580 REM MS(IDMAX)= AN ARRAY THAT STORES THE TRAVEL TIME BETWEEN POSITIONS.
590 REM NF$= THE FILE NAME WHERE THE DATA ARE TO BE STORED
600 REM OM= THE NUMBER OF OBSERVATIONS TO BE AVERAGED
610 REM PB= THE DATA REGISTER FOR THE VIC 20 USER PORT
620 REM PMAX= THE MAXIMUM NUMBER OF POSITIONS IN THE EXPERIMENT
630 REM PN= A COUNTER WHICH STORES THE PRESENT POSITIONAL VALUE IN A LOOP

```

```

610 REM PO= A VARIABLE WHICH STORES THE PRESENT POSITIONAL VALUE UNDER ANALYSIS
620 REM RT= A REAL VARIABLE USED AS A RUNNING TOTAL FOR THE CAPACITANCE
630 REM SM= A COUNTER USED TO PROCESS THE CAPACITANCE OBSERVATION
640 REM SS= A COUNTER USED TO INITIALIZE THE GP VALUE OF THE DATA ARRAY
650 REM T = AN EMPIRICALLY DERIVED MOTOR-ON TIME CONSTANT
660 REM TM(IDMAX)= AN ARRAY THAT STORES THE BEGINNING TIMES FOR EACH SAMPLING
670 REM TT= A COUNTER USED TO INITIALIZE THE PO VALUE OF THE DATA ARRAY
680 REM U= A DUTY CYCLE VARIABLE USED IN THE MANUAL MOTOR CONTROL LOOP
690 REM UU= A COUNTER USED TO INITIALIZE THE IDMAX VALUE OF THE DATA ARRAY
700 REM V= A DUTY CYCLE VARIABLE THAT IS THE TIME SUPPLEMENT OF U
710 REM XX= A COUNTER USED TO PRINT OUT THE GP VALUE OF THE DATA ARRAY
720 REM XS= A TEMPORARY VARIABLE USED TO MONITOR A DEPRESSED KEY
730 REM X= A COUNTER USED TO SEND THE GP VALUE OF THE DATA ARRAY TO DISK
740 REM Y= A COUNTER USED TO SEND THE PO VALUE OF THE DATA ARRAY TO DISK
750 REM YY= A COUNTER USED TO PRINT OUT THE IDMAX VALUE OF THE DATA ARRAY
760 REM Z= A COUNTER USED TO SEND THE IDMAX VALUE OF THE DATA ARRAY TO DISK
770 REM WB(GP)= A REAL ARRAY USED TO STORE WET BULB TEMPERATURE.
780 REM *****
790 REM
800 REM
810 REM
820 REM ***** BEGIN MAIN BODY *****
830 NFS="QWERTY":DR$="FORWARD":TEMP=1
840 BEENHERES="N"
850 PMAX= 4
860 IDMAX= 5
870 GMAX=10
880 OM=10:PN=1:GP=1
890 DIM MS(PMAX+1),D(GMAX,PMAX,IDMAX),TM(GMAX),WB(GMAX),DB(GMAX)
900 PB= 37138:DD=37136
910 REM ***** FILL AUTOMATIC DATA ARRAY *****
920 FOR JJ= 0 TO PMAX+1
930 READ MS(JJ)
940 NEXT JJ
950 DATA 546.522.0,486.0,438.0,330.0,312
960 RESTORE
970 REM ***** INITIALIZE DATA MATRIX *****
980 PRINT CHR$(147); " PLEASE WAIT."
990 PRINT " ":PRINT"INITIALIZING DATA MATRIX..."
1000 FOR SS= 1 TO GMAX
1010 FOR TT= 1 TO PMAX
1020 FOR UU= 1 TO IDMAX
1030 D(SS,TT,UU)=-1111
1040 NEXT UU
1050 NEXT TT
1060 NEXT SS
1070 POKE DD,0
1080 POKE PB,255
1090 IF GP>= GMAX THEN 2670
1100 PRINTCHR$(147)
1110 REM ***** ENVIRONMENTAL DATA SECTION *****

```

```

1120 PRINT" ENVIRONMENTAL DATA "
1130 PRINT"GP=";GP;"PN=";PN;"PO=";PO
1140 PRINT" ":PRINT"O) CONTINUE THE PROGRAM"
1150 PRINT"1) TIME OF STUDY = ";TM(GP)
1160 PRINT"2) WET BULB TEMP.= ";WB(GP)
1170 PRINT"3) DRY BULB TEMP.= ";DB(GP)
1180 PRINT" "
1190 PRINT"WHAT'S YOUR CHOICE":INPUT CH
1200 IF CH<=0 THEN 1270
1210 ON CH GOSUB 1230,1240,1250
1220 GOTO 1100
1230 PRINT"INPUT TIME":INPUT TM(GP):RETURN
1240 PRINT"INPUT WET BULB":INPUT WB(GP):RETURN
1250 PRINT"INPUT DRY BULB":INPUT DB(GP):RETURN
1260 PO=PN-1
1270 REM ***** ROTATION CONTROL MENU *****
1280 PRINT CHR$(147)
1290 PRINT" ROTATION CONTROL MENU ":PRINT" "
1300 PRINT" ":"GP=";GP;"PO=";PO;"PN=";PN:PRINT" "
1310 PRINT" ":PRINT"DO YOU WANT TO CONTROL MOTOR: "
1320 PRINT" "
1330 PRINT" M)ANUALLY"
1340 PRINT" A)UTOMATICALLY"
1350 PRINT" E)NTER DATA"
1360 PRINT" "
1370 IF BEENHERE$="Y" THENPRINT"YOU'VE MOVED THE MOTOR ALREADY"
1380 IF BEENHERE$="Y" THEN PRINT"YOU HAVEN'T ENTERED DATA YET"
1390 PRINT" ":PRINT" YOUR CHOICE IS ";
1400 INPUT MC$
1410 BEENHERE$="Y"
1420 IF MC$="M" THEN GOSUB 1460
1430 IF MC$="A" THEN GOSUB 1660
1440 IF MC$="E" THEN 2110
1450 GOTO 1270
1460 REM ***** MANUAL MOTOR PULSE CONTROL *****
1470 PRINT"***** MANUAL CONTROL *****"
1480 PRINT" A 'Q' STOPS THE MOTOR"
1490 T= 5
1500 REM O-TURNS ON 255-TURNS OFF
1510 REM AS U INCREASES THE ON CYCLE INCREASES
1520 POKE DD,0: POKE PB,255
1530 GET X$: IF X$="Q" THEN 1650
1540 V=VAL(X$)
1550 IF V=0 THEN 1570
1560 U=V: PRINT U
1570 REM ** THIS IS THE WAIT LOOP **
1580 FOR J=1 TO 7.5*T*(10-U)
1590 NEXT J
1600 POKE PB,0
1610 REM ** THIS IS THE RUNNING LOOP **
1620 FOR K=1 TO T*U

```

```

1630 NEXT K
1640 GOTO 1520
1650 RETURN
1660 REM ***** AUTOMATIC SUBROUTINE *****
1670 PRINT CHR$(147);" AUTOMATIC CONTROL ":PRINT " "
1680 PRINT"STATUS: ":PRINT " ":PRINT " "
1690 PRINT"GROUP #: ";GP
1700 PRINT"FILE: ";NF$
1710 PRINT"PRESENT POSITION: ";PO
1720 PRINT"DIRECTION: ";DR$
1730 PRINT" ":PRINT"R)ETURN TO EDITOR "
1740 PRINT"M)OVE TO NEXT POSITION":PRINT"WHAT IS YOUR CHOICE":INPUTMC$
1750 T=10
1760 POKEPB,0:REM ##### TURN ON #####
1770 FOR KK=1 TO 10
1780 NEXTKK
1790 POKE PB,255:REM ##### TURN OFF #####
1800 RT= 0:MAX=0:MIN=9999
1810 REM *****
1820 REM *
1830 FOR SM=1 TO OM: REM ***** AVERAGE CP LOOP *****
1840 REM *
1850 REM *****
1860 POKEPB,1
1870 SYS830:CP=PEEK(829)*3077+12*PEEK(828)+12:PRINTCP
1880 RT=RT+CP
1890 IF CP>MAX THEN MAX=CP
1900 IF CP< MIN THEN MIN=CP
1910 NEXT SM
1920 PRINT"MIN=";MIN;"MAX";MAX;"AV=";AV
1930 AV=RT/OM
1940 IF DR$="REVERSE" THEN 2010
1950 REM ***** FORWARD *****
1960 IF PO<0 THEN PO=0
1970 IF PO<0 THEN PN=1
1980 IF AV< MS(PO) THEN 2060
1990 T=8*MS(PO)-AV
2000 GOTO 1760
2010 REM ***** REVERSE *****
2020 PRINT"IM AT 6231"
2030 IF AV> MS(PO) THEN 2060
2040 T= 8*MS(PO)-AV
2050 GOTO 1760
2060 REM ***** DATA EDITOR *****
2070 POKE DD,0:POKE PB,255
2080 IF PO< 0 THEN 2420
2090 IF PO>PMAX THEN 2420
2100 D(GP,PO,5)=AV
2110 PRINT CHR$(147)
2120 IF PO > PMAX THEN 2560
2130 PRINT" DATA EDITING MENU ":PRINT " ":PRINT"GP=";GP;"PN=";PN;"PO=";PO

```

```

2140 PRINT " "
2150 PRINT"(0) CONTINUE THE RUN"
2160 PRINT"(1) FILE NAME= ";NF$
2170 PRINT"(2) RIGHT SIDE= ";D(GP,PO,1)
2180 PRINT"(3) LEFT SIDE= ";D(GP,PO,2)
2190 PRINT"(4) BOTTOM = ";D(GP,PO,3)
2200 PRINT"(5) TOP = ";D(GP,PO,4)
2210 PRINT"(6) TIME = ";TM(GP)
2220 PRINT"(7) WET B. TEMP.= ";WB(GP)
2230 PRINT"(8) DRY B. TEMP.= ";DB(GP)
2240 PRINT"(9) CAPACITANCE=";D(GP,PO,5);DR$;"PO=";PO;MS(PO);AV
2250 PRINT"(10) RETURN TO MOTOR CONTROL"
2260 PRINT"(11) CHANGE GP"
2270 PRINT " ":PRINT " ":PRINT"CHANGE WHAT VALUE":INPUT CH
2280 IF CH <=0 THEN 2420
2290 PRINT " "
2300 ON CH GOSUB 2320,2330,2340,2350,2360,2370,2380,2390,2400,1270,2410
2310 GOTO 2060
2320 PRINT"WHAT'S THE FILE NAME":INPUT NF$:RETURN
2330 PRINT"INPUT RIGHT SIDE":INPUT D(GP,PO,1) :RETURN
2340 PRINT"INPUT LEFT SIDE ":INPUT D(GP,PO,2) :RETURN
2350 PRINT"INPUT BOTTOM OF SPOT":INPUT D(GP,PO,3) :RETURN
2360 PRINT"INPUT TOP OF SPOT ":INPUT D(GP,PO,4) :RETURN
2370 PRINT"INPUT TIME OF STUDY":INPUT TM(GP):RETURN
2380 PRINT"INPUT WET BULB TEMPERATURE ":INPUT WB(GP):RETURN
2390 PRINT"INPUT DRY BULB TEMPERATURE":INPUT DB(GP):RETURN
2400 PRINT"INPUT CAPACITANCE ":INPUT D(GP,PO,5) :RETURN
2410 PRINT" INPUT GROUP":INPUT GP:RETURN
2420 REM ***** FILE I/O MENU *****
2430 PRINTCHR$(147)
2440 PRINT " FILE EDITOR":PRINT " ":PRINT"GP=";GP;"PO=";PO;"PN=";PN
2450 PRINT " "
2460 PRINT"(1) ALTER LAST SEQUENCE OF DATA"
2470 PRINT"(2) PRINT A HARD COPY OF PRESENT POSITION ":PRINT " "
2480 PRINT"(3) CONTINUE THE PROGRAM"
2490 PRINT"(4) QUIT THE PROGRAM":PRINT " "
2500 PRINT"(5) SEN DATA TO DISK"
2510 PRINT"(6) CHANGE PO & PN"
2520 PRINT"WHAT'S YOUR FILE CHOICE":INPUT HC
2530 ON HC GOTO 2110,2720,2560,2710,2850,2540
2540 PRINT"INPUT PO,PN":INPUT PO,PN
2550 GOTO 2430
2560 IF DR$="FORWARD"THEN PN=PN+1
2570 IF DR$="REVERSE"THEN PN=PN-1
2580 BEENHERE$="N"
2590 IF PN=PMAX+2 THEN 2640
2600 IF DR$="FORWARD"THEN 2630
2610 IF PN=0 THEN DR$="FORWARD"
2620 IF PO<0 THEN PN=1
2630 GOTO 1260
2640 DR$="REVERSE"

```

```

2650 GP= GP+1
2660 GOTO 1090
2670 PRINT"FILE NAME=";NF$
2680 PRINT"SAVE DATA TO DISK UNDER THIS NAME":INPUT YN$
2690 IF LEFT$(YN$,1)= "Y" THEN 2850
2700 GOTO 2420
2710 END
2720 REM ***** PRINTS OUT DATA *****
2730 OPEN 1,4
2740 CMD1
2750 PRINT"GROUP # = ";GP
2760 FOR XX= 1 TO PO
2770 FOR YY= 1 TO IDMAX
2780 PRINTXX;YY;D(GP,XX,YY)
2790 NEXT YY
2800 NEXT XX
2810 PRINT#1
2820 CLOSE1
2830 PRINT"DATA HAS BEEN PRINTED OUT ":INPUTZ
2840 GOTO 2420
2850 REM ***** SEND DATA TO DISK *****
2860 PRINT"NAME OF FILE IS ";NF$
2870 OPEN 11,8,11,"O:"+NF$+"S,W"
2880 PRINT#11,GMAX
2890 PRINT#11,PMAX
2900 PRINT#11,IDMAX
2910 FOR X= 1 TO GMAX
2920 PRINT#11,TM(X)
2930 PRINT#11,WB(X)
2940 PRINT#11,DB(X)
2950 FOR Y= 1 TO PMAX
2960 FOR Z= 1 TO IDMAX
2970 PRINT#11,D(X,Y,Z)
2980 NEXT Z
2990 NEXT Y
3000 NEXT X
3010 CLOSE 11
3020 REM ***** Z IS USED HERE TO TEMPORARILY STOP THE PROGRAM *****
3030 PRINT"WAIT ":INPUT Z
3040 REM ***** UPDATE DIRECTORY *****
3050 PRINT"NAME OF OLD DIRECTORY",BF$
3060 OPEN 11,8,11,"O:"+BF$+"S,W"
3070 INPUT#11,FMAX
3080 DIM DIS(FMAX+1)
3090 FOR L=1 TO FMAX
3100 INPUT#11,DIS(L)
3110 PRINT DIS(L)
3120 NEXT L
3130 DIS(FMAX+1)=NF$
3140 CLOSE11
3150 AF$="D"+NF$:PRINT "NAME OF NEW DIRECTORY IS ":AF$

```



```
3160 OPEN 11,8,11,"O:"+AF$+"S,W"  
3170 PRINT#11,DI$(LO)  
3180 NEXT LO  
3190 CLOSE 11  
3200 GOTO 2420
```

Fig. E.4. Geometry processing program

```

PROGRAM ANGINTERCEPT;
CONST
  PI= 3.1415926;
  TOL=0.1;

VAR
  MD : ARRAY [1..6,1..8] OF REAL;
  X (* THE X VALUE OF THE SPOT *),
  Y (* THE Y VALUE OF THE SPOT *),
  C (* USED TO STOP EXECUTION OR LEAVE THE PROGRAM *),
  AX (* THE X VALUE OF THE LONGEST END POINT OF THE ROTOR *),
  BX (* " " " " " POINT OF LIGHT BEAM INTERSECTION WITH SHAFT MIRROR *),
  CX (* " " " " " " " " " " " FINE ADJ. " *),
  DX (* " " " " " " " " " " " COLLECTOR " *),
  EX (* " " " " " " " " " " " WALL " *),

  AY (* THE Y VALUE OF THE LONGEST END POINT OF THE ROTOR *),
  BY (* " " " " " " " " " " " POINT OF LIGHT BEAM INTERSECTION WITH SHAFT MIRROR *),
  CY (* " " " " " " " " " " " FINE ADJ. " *),
  DY (* " " " " " " " " " " " COLLECTOR " *),
  EY (* " " " " " " " " " " " WALL " *),

  PX (* THE X CO-ORDINATE OF THE SHAFT CENTER *),
  PY (* THE Y CO-ORDINATE OF THE SHAFT CENTER *),
  D (* THE DISTANCE FROM THE SHAFT CENTER TO THE LONGEST END POINT OF THE ROTOR *),

  TSM,TSMR (* THE THETA ANGLES OF THE SHAFT MIRROR & ITS REFLECTION (IN RADIANS) *),
  TFA,TFAR (* " " " " " " FINE ADJ. " & " " " " " *),
  TCM,TCMR (* " " " " " " COLLECT. " & " " " " " *),
  MSM,BSM (* THE SLOPE AND THE Y INTERSECTION POINT OF THE SHAFT MIRROR *),
  MSMR,BSMR (* " " " " " " " " " " " & REFLECT *),
  MFAR,BFAR (* " " " " " " " " " " " FINE ADJ. " " " " *),
  MCMR,BCMR (* " " " " " " " " " " " COLLECTOR " " " *),

  HIX,ESTX,LOX (* THE HIGH, ESTIMATED & LOW VALUES OF THE SPOT ON THE WALL *),
  HIANG,ESTANG,LOANG (* THE HIGH, ESTIMATED & LOW VALUES OF A POS'N.'S ANGLE *),
  XDIFF,ADIFF (* THE DIFFERENCE BETWEEN A POS'N.'S ACTUAL & CALC. X AND ANG. VALUE *),
  DELTA (* THE ANGLE BETWEEN THE SHAFT MIRROR & THE ROTOR'S FINS *),
  THETA (* THE ANGLE ENTERED BY THE USER TO DETERMINE IF THE CALC. X
    IS WITHIN RANGE OF THE ACTUAL DATA *) : REAL;

  CTR (* A COUNTER USED TO FIND AN ANGLE THETA FROM AN ENTERED X *),
  POSN (* A POSITION COUNTER *) : INTEGER;

FUNCTION CONVERT(ENTVAR,MULFACTOR,OFFSET:REAL):REAL;
BEGIN
  CONVERT := (ENTVAR*MULFACTOR)+OFFSET;
END;

FUNCTION TAN(Q:REAL):REAL;
BEGIN
  TAN := (SIN(Q)/COS(Q));
END;

FUNCTION DEGTO RAD(EVAR:REAL):REAL;
BEGIN
  DEGTO RAD:=CONVERT(EVAR,PI/180,0);
END;

FUNCTION RADTO DEG(EVAR:REAL):REAL;
BEGIN
  RADTO DEG := CONVERT(EVAR,180/PI,0);
END;

```

```

FUNCTION BPTSLOPE(XI,YI,MI :REAL):REAL;
BEGIN
  BPTSLOPE := YI-(MI*XI);
END;

PROCEDURE PTOFINTERSECT(M1,B1,M2,B2:REAL;VAR XI,YI :REAL);
BEGIN
  XI:= (B1-B2)/(M2-M1);
  YI:=(M2*XI)+B2;
END;

PROCEDURE FINDLINES;
VAR
  X1,Y1,X2,Y2,B,M,AA : REAL;
  R,C : INTEGER;

BEGIN
  MD[1,1]:=-3180;MD[1,2]:= 79;MD[1,3]:=-3202;MD[1,4]:= 132;
  MD[2,1]:=-3201;MD[2,2]:=150;MD[2,3]:=-3227;MD[2,4]:= 201;
  MD[3,1]:=-3298;MD[3,2]:=262;MD[3,3]:=-3341;MD[3,4]:= 311;
  MD[4,1]:=-3418;MD[4,2]:= 92;MD[4,3]:=-3476;MD[4,4]:= 127;
  MD[5,1]:=-7430;MD[5,2]:=785;MD[5,3]:=-7391;MD[5,4]:=1912;
  MD[6,1]:= 0;MD[6,2]:= 0;MD[6,3]:= 7;MD[6,4]:= 81;
  FOR R:= 1 TO 6 DO
  BEGIN
    (* FIND SLOPE & CONVERT TO AN ANGLE *)
    MD[R,5]:=RADTODEG(ARCTAN((MD[R,4]-MD[R,2])/(MD[R,3]-MD[R,1])));
    (* FIND Y INTERCEPT *)
    MD[R,6]:=MD[R,4]-(TAN(DEGTORAD(MD[R,5]))*MD[R,3]);
    (* FIND INITIAL ANGLE IN DEGREES *)
    MD[R,7]:=RADTODEG(ARCTAN((MD[R,2]+19)/(MD[R,1]+3367)));
    (* FIND TERMINAL ANGLE IN DEGREES *)
    MD[R,8]:=RADTODEG(ARCTAN((MD[R,4]+19)/(MD[R,3]+3367)));
    (* IF ANGLES ARE NEGATIVE ADD 180 *)
    IF MD[R,5] < 0 THEN MD[R,5]:=180+MD[R,5];
    IF MD[R,7] < 0 THEN MD[R,7]:=180+MD[R,7];
    IF MD[R,8] < 0 THEN MD[R,8]:=180+MD[R,8];
    WRITE(R,' SLOPE=',MD[R,5]);
    WRITELN;
    WRITELN('INTERCEPT=',MD[R,6]);
    WRITELN;
    WRITELN('IA= ',MD[R,7],' TA= ',MD[R,8]);
    (* CONVERT ALL DEGREE ANGLES BACK TO RADIAN ANGLES *)
    MD[R,5]:=DEGTORAD(MD[R,5]);
    MD[R,7]:=DEGTORAD(MD[R,7]);
    MD[R,8]:=DEGTORAD(MD[R,8]);
    WRITELN;
  END;
END;

PROCEDURE FINDRAYPATH;
BEGIN
  READLN(C);

  WRITELN;
  MFAR := TAN(TFAR);
  BFAR := BPTSLOPE(CX,CY,MFAR);
  PTOFINTERSECT(MFAR,BFAR,MD[5,5],MD[5,6],DX,DY);
  WRITELN('MFAR= ',MFAR,RADTODEG(ARCTAN(MFAR)));
  WRITELN('BFAR= ',BSMR);
  WRITELN('DX= ',DX,' DY= ',DY);
  WRITELN;
  MCMR := TAN(TCMR);

```

```

BCMR := BPTSLOPE(DX,DY,MCMR);
PTOFINTERSECT(MCMR,BCMR,MD[6,5],MD[6,6],EX,EY);
Writeln('MCMR= ',MCMR,RADTODEG(ARCTAN(MCMR)));
Writeln('BCMR= ',BCMR);
Writeln('EX= ',EX,' EY= ',EY);
Writeln;
ESTX := (64/250*EX) + 1.0;
Writeln(ESTX);
END;

PROCEDURE FINDTHETA;
BEGIN
  CTR := 0;
  WHILE (XDIFF>TOL) OR (CTR>100) DO
    BEGIN
      CTR:=CTR+1;
      IF ESTX>X THEN
        BEGIN
          HIANG := ESTANG;
          LOANG := CONVERT(ADIFF,X/ESTX,LOANG);
        END;

      IF ESTX<X THEN
        BEGIN
          LOANG:=ESTANG;
          HIANG:=CONVERT(ADIFF,ESTX/X,LOANG);
        END;

      Writeln(POSN,CTR,' HIANG= ',HIANG,' HIX= ',HIX);
      Writeln;
      Writeln(' ESTANG= ',ESTANG,' ESTX= ',ESTX);
      Writeln;
      Writeln(' LOANG= ',LOANG,' LOX= ',LOX);
      Writeln;
    END;
  END;

BEGIN (* MAIN BODY *)
FINDLINES;
Writeln('GO ON ');
READLN(C);
WHILE C<0 DO
  BEGIN
    WRITE('GO ON ');
    READLN(C);
    Writeln('WHAT POSITION');
    READLN(POSN);
    READLN(THETA);
    THETA := DEGTORAD(THETA);
    PX := -3367;
    PY := -19;
    D := 24.13;
    DELTA := ARCTAN(0.136);
    Writeln('DELTA= ',DELTA,RADTODEG(DELTA));
    TSM := THETA-DELTA;
    Writeln('TSM= ',TSM,RADTODEG(TSM));
    TSMR := 2*TSM;
    Writeln('TSMR= ',TSMR,RADTODEG(TSMR));
    TFA := MD[POSN,5];
    Writeln('TFA= ',TFA,RADTODEG(TFA));
    TFAR := (2*TFA)-TSMR;
    Writeln('TFAR= ',TFAR,RADTODEG(TFAR));
    TCM := MD[5,5];
    Writeln('TCM= ',TCM,RADTODEG(TCM));
    TCMR := (2*TCM)-TFAR;
  
```

```

WRITELN('TCMR= ',TCMR,RADTODEG(TCMR));
WRITELN;
AX := (D*COS(THETA))+PX;
AY := (D*SIN(THETA))+PY;
WRITELN('AX= ',AX,' AY= ',AY);
MSM := TAN(TSM);
BSM := BPTSLOPE(AX,AY,MSM);
PTOFINTERSECT(MSM,BSM,0,0,BX,BY);
WRITELN('MSM= ',MSM,RADTODEG(ARCTAN(MSM)));
WRITELN('BSM= ',BSM);
WRITELN('BX= ',BX,' BY= ',BY);
WRITELN;
MSMR := TAN(TSMR);
BSMR := BPTSLOPE(BX,BY,MSMR);
PTOFINTERSECT(MSMR,BSMR,TAN(MD[POSN,5]),MD[POSN,6],CX,CY);
WRITELN('MSMR= ',MSMR,RADTODEG(ARCTAN(MSMR)));
WRITELN('BSMR= ',BSMR);
WRITELN('CX= ',CX,' CY= ',CY);
END;
END.

```

Fig. E.5. Environmental experiment program

```

100 REM
110 REM
120 REM
130 REM
140 REM
150 REM
160 REM
170 :
180 :
190 :
200 REM ***** VARIABLE DICTIONARY *****
210 REM
220 REM AV(SAMPLE #,F)= A REAL ARRAY USED TO STORE CAPACITANCE AND TEMPERATURE
230 REM CMAX = MAX # OF CAPACITORS
240 REM CT= CYCLE TIME OR THE TIME BETWEEN EACH READING
250 REM DB= DRY BULB TEMPERATURE
260 REM G= PRESENT CAPACITOR READING
270 REM H$= HUMIDITY LEVEL-EITHER HIGH OR LOW
280 REM HT= THE # OF READINGS BETWEEN HUMIDITY READINGS
290 REM JJ= THE NUMBER OF SECONDS IN THE COUNTUP PERIOD
300 REM MM= THE NUMBER OF MINUTES
310 REM OO= A TIME INITIALIZATION VARIABLE
320 REM P$= THE HUMIDTY LEVEL FOR THIS RUN
330 REM QI= A COUNTER USED TO SEN CAPACITANCE DATA TO DISK FILE
340 REM QQ= A COUNTER USED TO SEND A READING NUMBER TO DISK FILE
350 REM R= PRESENT SAMPLE NUMBER
360 REM RDMAX=MAX # OF READINGS
370 REM RDMAX=MAX # OF READINGS
380 REM SMAX= OBSERVATION SIZE TO BE AVERAGED
390 REM TEMP= A RUNNING TOTAL OF CAPACITANCE OBSERVATIONS
400 REM WB= WET BULB TEMPERATURE
410 REM Z= A COUNTER USED TO AVERAGE SMAX NUMBER OF OBSERVATIONS
420 REM *****
430 :
440 OO=TI: REM ***** INITIALIZE THE TIMER *****
450 CT=2.0:RDMAX=84:CMAX=3:SMAX=350
460 HT=04
470 DIM AV(RDMAX,CMAX+2)
480 PRINT"WHAT'S WB,DB ":INPUT WB,DB
490 :
500 REM ***** BEGIN MAIN BODY *****
510 FOR R=1 TO RDMAX
520 REM ***** COUNTUP READING LOOP *****
530 REM INITIALIZE SECOND & MINUTE COUNTERS, ABSOLUTE YIME LABELS
540 TM=TI:X$=TI$:JJ=0:MM=0
550 :
560 REM ***** CHECK TO SEE IF A SECOND HAS ADVANCED *****
570 IF MID$(TI$,5,2)=MID$(X$,5,2) THEN 730
580 PRINT"":PRINT"THE TIME IS ":PRINT" ":PRINT" ":PRINT" "
590 PRINT"R=";R;"TI$=";TI$
600 PRINT((TI-OO)/(CT*3600))-INT((TI-OO)/(CT*3600))

```



```

610 :
620 REM ***** CALCULATE SECONDS *****
630 JJ=INT((TI-TM)/60)-(MM*60)
640 :
650 REM ***** CARRY A MINUTE *****
660 REM ***** IF A MINUTE IS CARRIED, THEN REINITIALZE SECONDS *****
670 IF JJ>60 THEN MM=MM+1
680 IF JJ>60 THEN JJ=0
690 PRINTMM;" MIN " ;JJ;" SEC "
700 XS=TIS
710 :
720 REM ***** CHECK TO SEE IF CYCLE TIME HAS ENDED *****
730 IF ((TI-00)/(CT*3600))-INT((TI-00)/(CT*3600)) >0 THEN 550
740 :
750 REM ***** MONITOR CAPACITORS *****
760 REM 854=OUTPUT OF 555 TIMER OR INPUT OF VIC I/O PORT
770 FOR G=1 TO CMAX
780 TEMP=0
790 POKE 849,1
800 POKE 854,2^G
810 POKE 844,(254)
820 :
830 REM ***** AVERAGE MANY OBSERVATIONS *****
840 FOR Z=1 TO SMAX
850 POKE37138,1
860 SYS830:CP= PEEK(829)*3077+12*PEEK(828)+12
870 PRINT"R=";R;"G=";G;"Z=";Z
880 TEMP=TEMP+CP
890 NEXT Z
900 :
910 REM ***** STORE SAMPLE DATA *****
920 AV(R,G)=TEMP/SMAX
930 AV(R,0)= VAL(TIS)
940 AV(R,4)= WB
950 AV(R,5)= DB
960 PRINT"AV(";R;G;")= ";AV(R,G)
970 NEXT G
980 :
990 REM ***** TURN ON AUDITORY TONE *****
1000 IF(R/HT)-INT(R/HT)=0 THEN POKE 36878,15:POKE 36875,231
1010 IF(R/HT)-INT(R/HT)=0 THEN PRINT "WHAT'S WB,DB ":INPUT WB,DB
1020 IF(R/HT)-INT(R/HT)=0 THEN POKE 36878,0
1030 REM ***** TURN OFF AUDITORY TONE *****
1040 :
1050 REM ***** PRINT DATA *****
1060 OPEN 1,4
1070 CMD1
1080 PRINT R;AV(R,0);AV(R,1);AV(R,2);AV(R,3);AV(R,4);AV(R,5)
1090 PRINT#1
1100 CLOSE 1,4
1110 NEXT R

```

```
1120 :
1130 REM ***** SEND DATA TO DISK *****
1140 PRINT"WHAT FILE NAME DO YOU WANT":INPUT NFS
1150 PRINT"IS ";NFS;"WHAT YOU WANT":INPUT YNS:IF LEFTS(YNS,1)<>"Y" THEN 1140
1160 OPEN 11,8,11,"O:"+NFS+"S,W"
1170 PRINT#11,RDMAX
1180 PRINT#11,CMAX+2
1190 FOR QQ= 1 TO RDMAX
1200 FOR QI= 0 TO CMAX+2
1210 PRINT#11,AV(QQ,QI)
1220 NEXT QI
1230 NEXT QQ
1240 CLOSE 11
1250 END
```

Fig. E.6. Relative humidity calculation program

```

100 REM
110 REM
120 REM
130 REM
140 REM
150 REM
160 REM
170 :
180 :
190 :
200 REM ***** VARIABLE DICTIONARY *****
210 REM SUBSCRIPT 1 IS DRY BULB
220 REM SUBSCRIPT 2 IS WET BULB
230 REM AP= ATMOSPHERIC PRESSURE
240 REM AS= THE DECIMAL FRACTION OF THE INTERPOLATED DEW POINT TEMPERATURE
250 REM D(DB,TEMPERATURE DATA)= THE DATA STORAGE ARRAY
260 REM DB= THE DRY BULB TEMPERATURE
270 REM DD= THE DENOMINATOR FOR THE DEWPT INTERPOLATION LOOP
280 REM DMAX= THE MAXIMUM NUMBER OF TEMPERATURES IN THE DATA TABLE OF THIS PGM.
290 REM DP=DRY BULB VAPOR PRESSURE
300 REM DP1= THE WATER PRESSUE AT A GIVEN DRY BULB TEMP
310 REM HF2= ENTHALPY OF SAT. LIQUID FOR WET BULB
320 REM HM2= ENTHALPY OF EVAPORATION FOR WET BULB. M IS FOR MIXTURE. HM2 IS HFG2
    IN TBL
330 REM JU= USED TO CHOOSE THE LOWER TEMPERATURE LIMIT FOR DEWPT. INTERPOLATION
340 REM K=18/28.966
350 REM    18 IS MOL WT. OF H2O.
360 REM    28.966 IS MOL WT OF STANDARD AIR
370 REM MP2= THE WATER VAPOR PRESSURE AT A GIVEN WET BULB TEMP
380 REM NN= THE NUMERATOR FOR THE INTERPOLATION LOOP
390 REM PW= PARTIAL PRESSURE OF WATER VAPOR
400 REM R= AN INDEX VARIABLE USED TO SELECT DATA FOR A GIVEN TEMPERATURE
410 REM TT= A COUNTER USED TO DETERMINE THE INTERPOLATED DEWPT.
420 REM W1= HUMIDITY RATIO OF THE ATMOSPHERE
430 REM W2=HUMIDITY RATIO OF WET BULB TEMP
440 REM WB= WET BULB TEMPERATURE
450 REM XX= A COUNTER USED TO FILL THE TEMPERATURE DIMENSION OF THE DATA ARRAY
460 REM YY= A COUNTER USED TO FILL INDIVIDUAL DATA IN D FOR A GIVEN TEMPERATURE
470 REM *****
480 :
490 :
500 :
510 REM ***** INITIALIZE VARIABLES *****
520 K=18/28.966
530 AP=14.7:WB=-999:DB=-999
540 DMAX=38: DIM D(DMAX,5)
550 FOR XX=1 TO DMAX
560 FOR YY=1 TO 5
570 READ D(XX,YY)
580 PRINT"D(";XX;YY;";";D(XX,YY)
590 NEXT YY
600 NEXT XX

```

```

610 RESTORE
620 :
630 REM ***** MAIN BODY *****
640 PRINT "INPUT WB,DB"
650 INPUT WB,DB
660 IF (WB=-999 OR DB=-999) THEN 1040
670 FOR R=1 TO DMAX
680 IF D(R,1)=WB THEN MP2= D(R,2)
690 IF D(R,1)=WB THEN HF2= D(R,3)
700 IF D(R,1)=WB THEN HM2= D(R,4)
710 IF D(R,1)=DB THEN DP1= D(R,2)
720 IF D(R,1)=DB THEN HG1= D(R,5)
730 PRINT "R=";R
740 PRINT WB,DB,DP1,MP2,HF2,HM2,HG1
750 NEXT R
760 IF (DP1<=0 OR MP2<=0) THEN PRINT "THESE VALUES ARE MISSING FROM THE DATA BA
SE"
770 PRINT " "
780 IF (DP1<=0 OR MP2<=0) THEN 640
790 PRINT "AT 475";WB,DB,DP1,MP2,HF2,HM2,HG1
800 REM ***** WORKING EQUATIONS *****
810 W2=K*(MP2/(AP-MP2))
820 W1=((W2*HM2)-.24*(DB-WB))/(HG1-HF2)
830 PW=(W1/K*AP)/(1+(W1/K))
840 RH=PW/DP1
850 PRINT " "
860 PRINT "W2=";W2;"W1=";W1;"PW=";PW;"RH=";RH
870 JU=0:PRINT " "
880 REM ***** INTERPOLATE DEWPOINT TEMPERATURE *****
890 FOR TT= 1 TO DMAX
900 IF D(TT,2)> PW THEN 920
910 GOTO 960
920 IF JU=1 THEN 960
930 JU=1:NN=PW-D(TT-1,2):DD=D(TT,2)-D(TT-1,2):PRINTNN;DD
940 JU=1:AS=NN/DD
950 PRINT "AS=";AS;"TEMP=";AS+D(TT-1,1)
960 NEXT TT
970 REM *****
980 :
990 :
1000 :
1010 PRINT WB,DB,DP1,MP2,HF2,HM2,HG1
1020 WB=0:DB=0:DP1=0:MP2=0:HF2=0:HM2=0:HG1=0:W1=0:W2=0:PW=0:RH=0
1030 GOTO 640
1040 END
1050 DATA 55,.2140,23.07,1062.4,1085.5
1060 DATA 56,.2219,24.08,1061.9,1085.9
1070 DATA 57,.2301,25.08,1061.3,1086.4
1080 DATA 58,.2386,26.08,1060.7,1086.8
1090 DATA 59,.2473,27.08,1060.2,1087.2
1100 DATA 60,.2563,28.08,1059.6,1087.7
1110 DATA 61,.2655,29.09,1059.0,1088.1

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1120 DATA 62,.2751,30.09,1058.5,1088.6  
1130 DATA 63,.2850,31.09,1057.9,1089  
1140 DATA 64,.2952,32.09,1057.3,1089.4  
1150 DATA 65,.3057,33.09,1056.8,1089.9  
1160 DATA 66,.3165,34.09,1056.2,1090.3  
1170 DATA 67,.3276,35.09,1055.6,1090.7  
1180 DATA 68,.3391,36.09,1055.1,1091.2  
1190 DATA 69,.3510,37.09,1054.5,1091.6  
1200 DATA 70,.3632,38.09,1054.0,1092  
1210 DATA 71,.3758,39.09,1053.4,1092.5  
1220 DATA 72,.3887,40.09,1052.8,1092.9  
1230 DATA 73,.4021,41.09,1052.3,1093.4  
1240 DATA 74,.4158,42.09,1051.7,1093.8  
1250 DATA 75,.4300,43.09,1051.1,1094.2  
1260 DATA 76,.4446,44.09,1050.6,1094.7  
1270 DATA 77,.4596,45.09,1050.0,1095.1  
1280 DATA 78,.4750,46.09,1049.5,1095.5  
1290 DATA 79,.4909,47.09,1048.9,1096.0  
1300 DATA 80,.5073,48.09,1048.3,1096.4  
1310 DATA 81,.5241,49.09,1047.7,1096.8  
1320 DATA 82,.5414,50.08,1047.2,1097.3  
1330 DATA 83,.5593,51.08,1046.6,1097.7  
1340 DATA 84,.5776,52.08,1046.0,1098.1  
1350 DATA 85,.5964,53.08,1045.5,1098.6  
1360 DATA 86,.6158,54.08,1044.9,1099.0  
1370 DATA 87,.6357,55.08,1044.4,1099.9  
1380 DATA 88,.6562,56.07,1043.8,1099.9  
1390 DATA 89,.6772,57.07,1043.2,1100.3  
1400 DATA 90,.6988,58.07,1042.7,1100.7  
1410 DATA 91,.7211,59.07,1042.1,1101.2  
1420 DATA 92,.7439,60.06,1041.5,1101.6